Electron-Capture Delayed Fission (ECDF) in the Pb region

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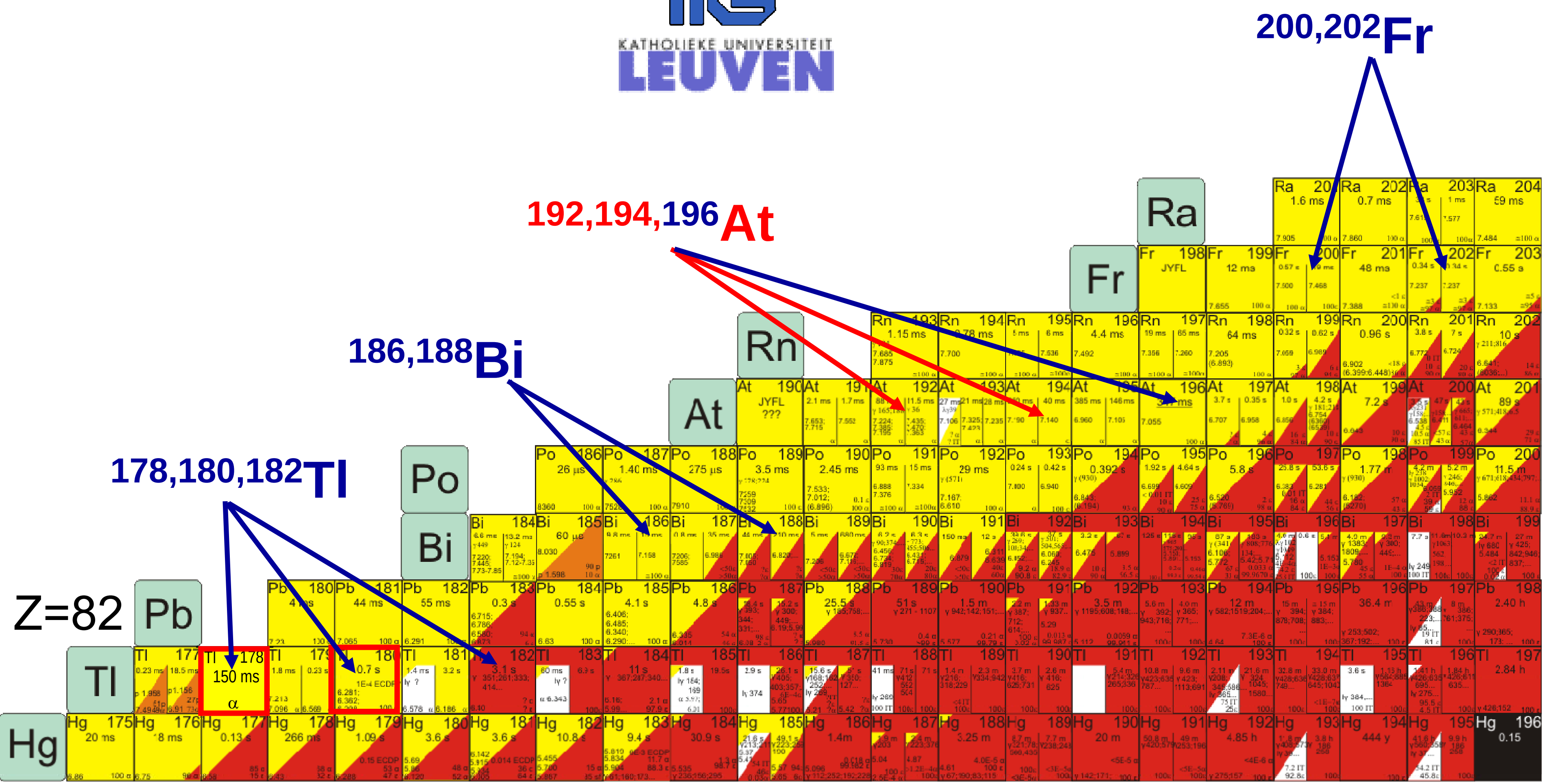

Collaboration

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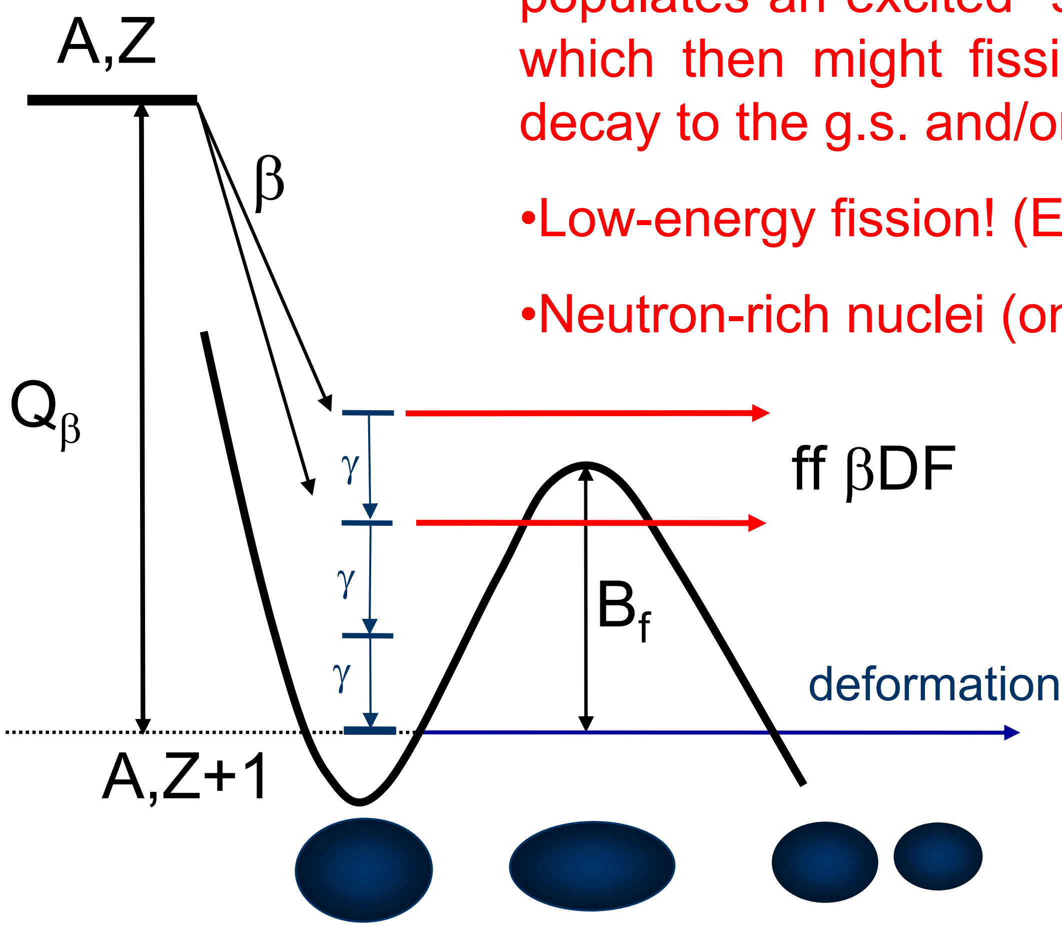
Plus many new collaborators for the future experiments at ISOLDE and other setups

Outlook

- Beta-delayed fission and Electron-Capture Delayed Fission-what it is and why?
- Earlier ECDF studies in the U and Pb regions
- ECDF identification in ^{192,194}At at SHIP
- Future plans in the Lead region

β-Delayed Fission (βDF, $T_{1/2}(ff)=T_{1/2}(\beta)$)

- 2 step process: β decay of a parent (A,Z) nucleus populates an excited state in the (A,Z+1) daughter , which then might fission (in competition with the γ decay to the g.s. and/or neutron emission)
- Low-energy fission! (E*~5-10 MeV)
- Neutron-rich nuclei (only 5 candidates known so far)

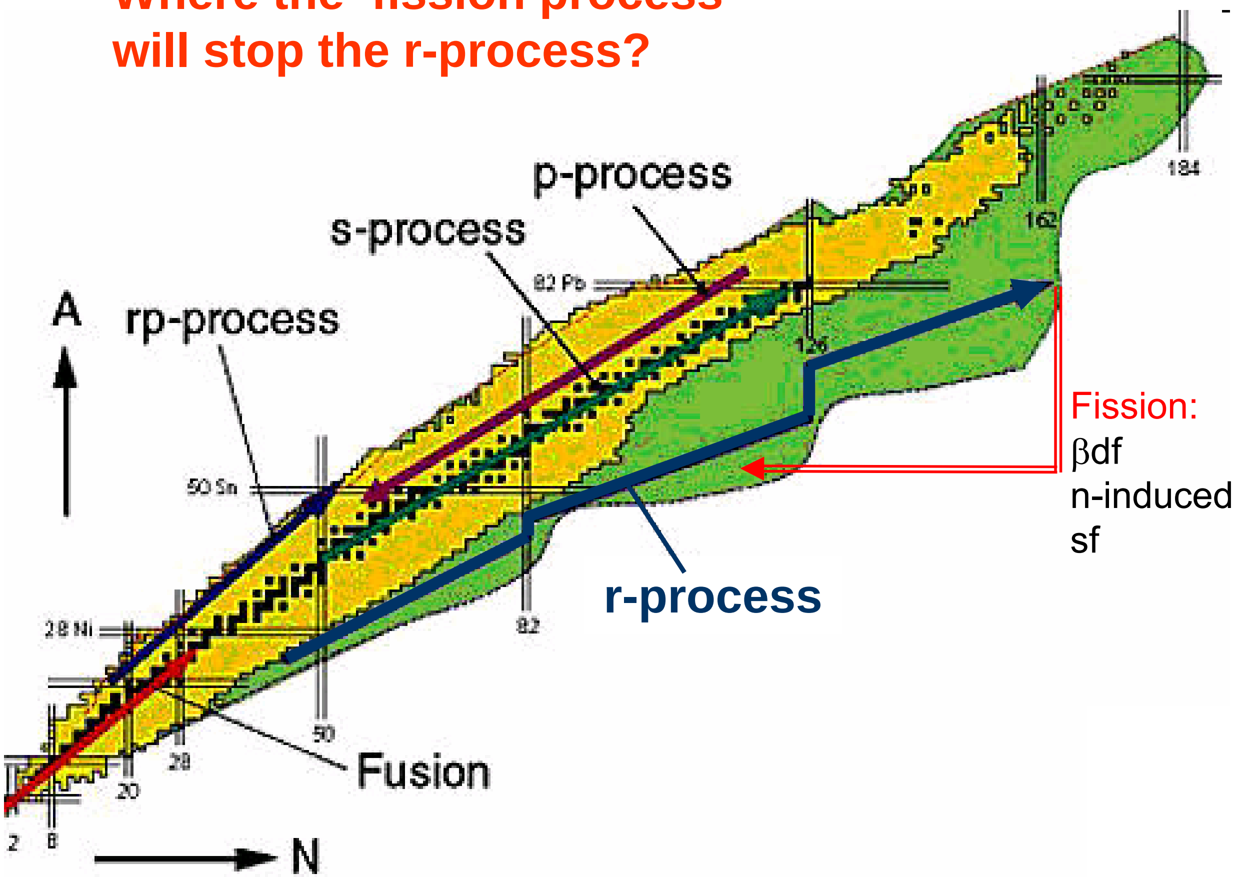


β-delayed Fission and r-process Nucleosynthesis

End point of r-process?
I.Panov et al, NPA747 (2005) 633

Trans-Uranium elements?
Cowan et al, Phys. Rep. 208 (1991) 267

Where the fission process will stop the r-process?



Fission cycling: **Fission products can serve as seed for the r-process!**
I. Panov et al, NPAA747 (2005) 633

r-process to the region with A>250

Fission: βdf n-induced, sf

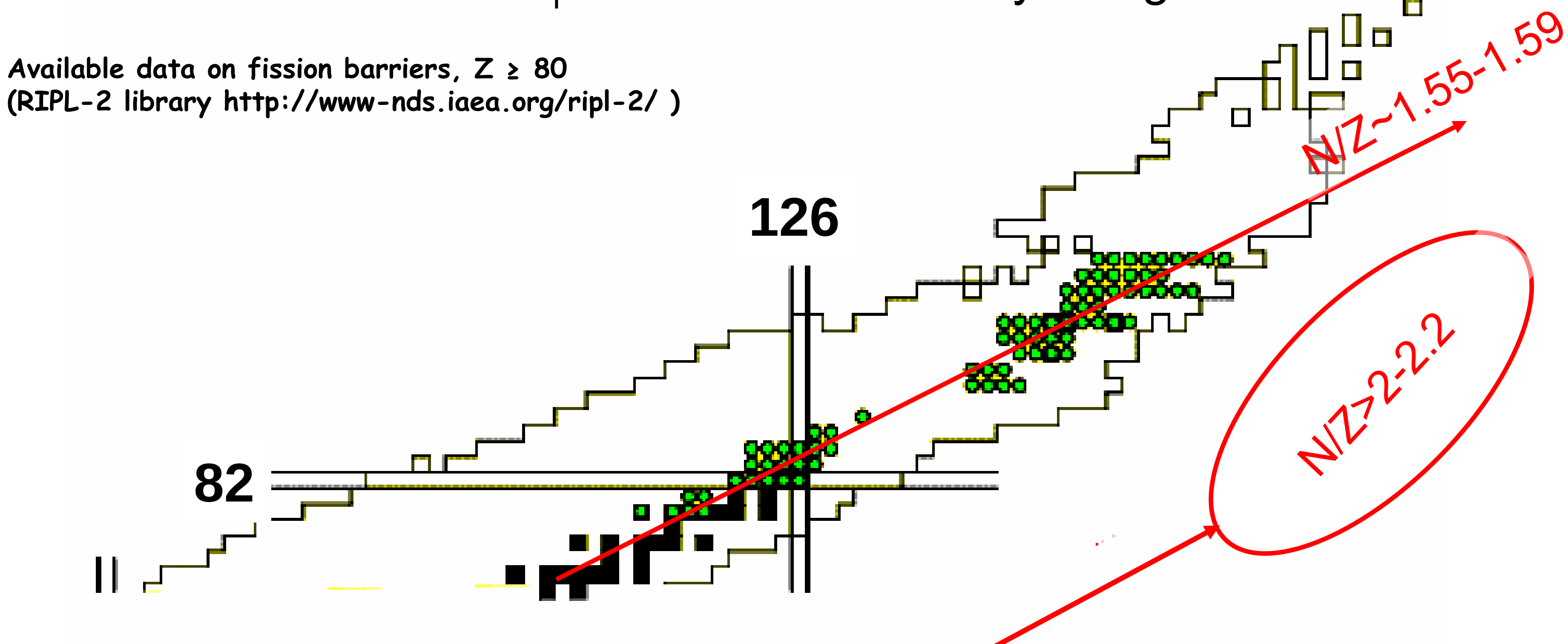
Fission A→A/2 ~125

r-process

Need fission data for very heavy exotic nuclei!

Example: Fission barriers - what do we know about them?

- Experimentally fission barriers B_f are known only in the vicinity of the beta stability line (e.g. N/Z(^{238}U)=1.59)
- Theoretical models for B_f have been 'tuned' by using these data

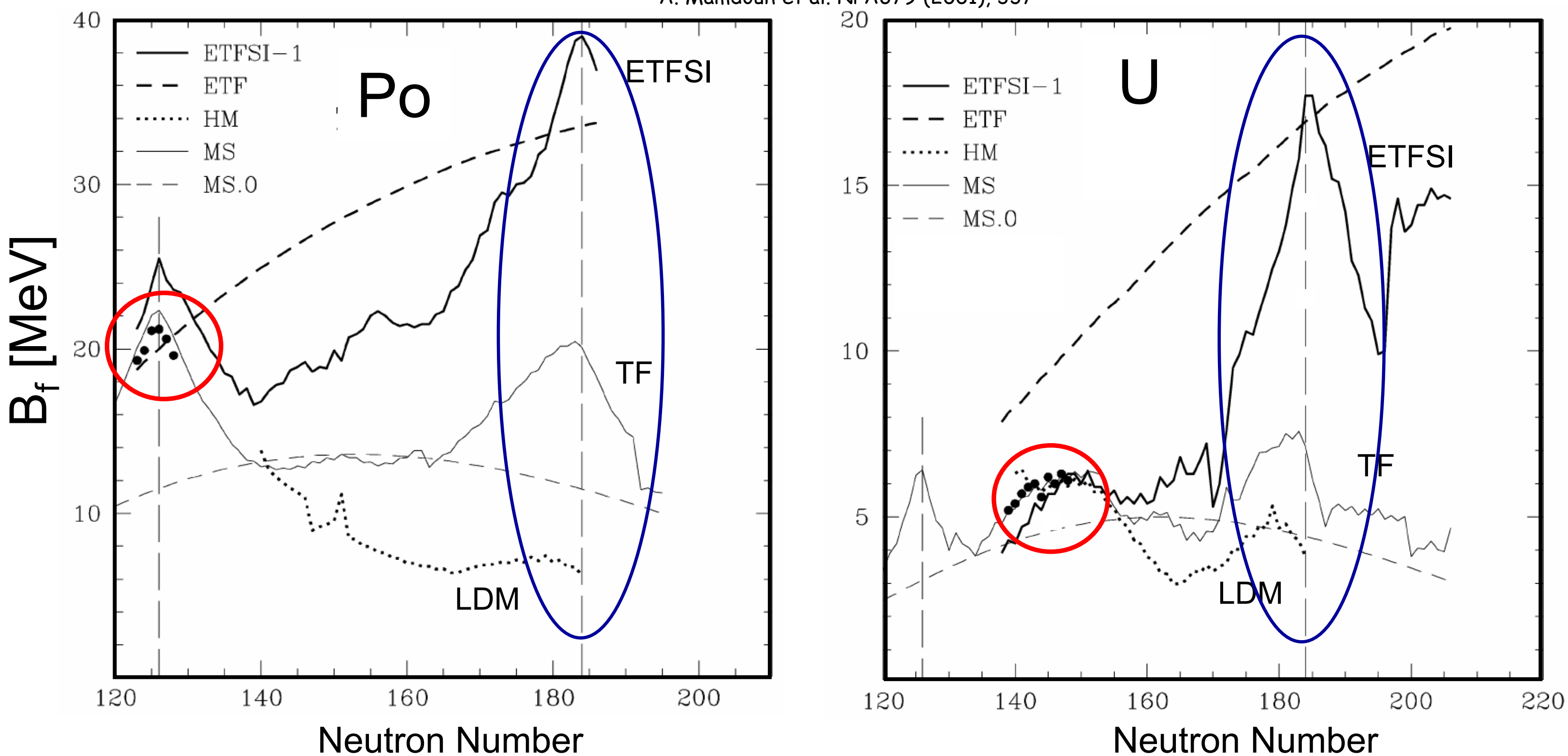


- For the r-process calculations we need fission data far away from stability: e.g. ^{260}Po or ^{270}U (N/Z>2!) – they might not be accessible in the Lab at all! – Use calculations?

Fission Barrier Calculations for the r-process nuclei

Full symbols – experimental data
Lines – calculations (LDM,TF, ETFSI)

A. Mamdouh et al. NPA679 (2001), 337



- Good agreement between $B_{f,cal}$ and $B_{f,exp}$ for nuclei close to stability
- Large disagreement far of stability (both on n-def. and n-rich sides)
- Need measured fission data far of stability to 'tune' fission models

Fission Barrier Calculations for the r-process nuclei

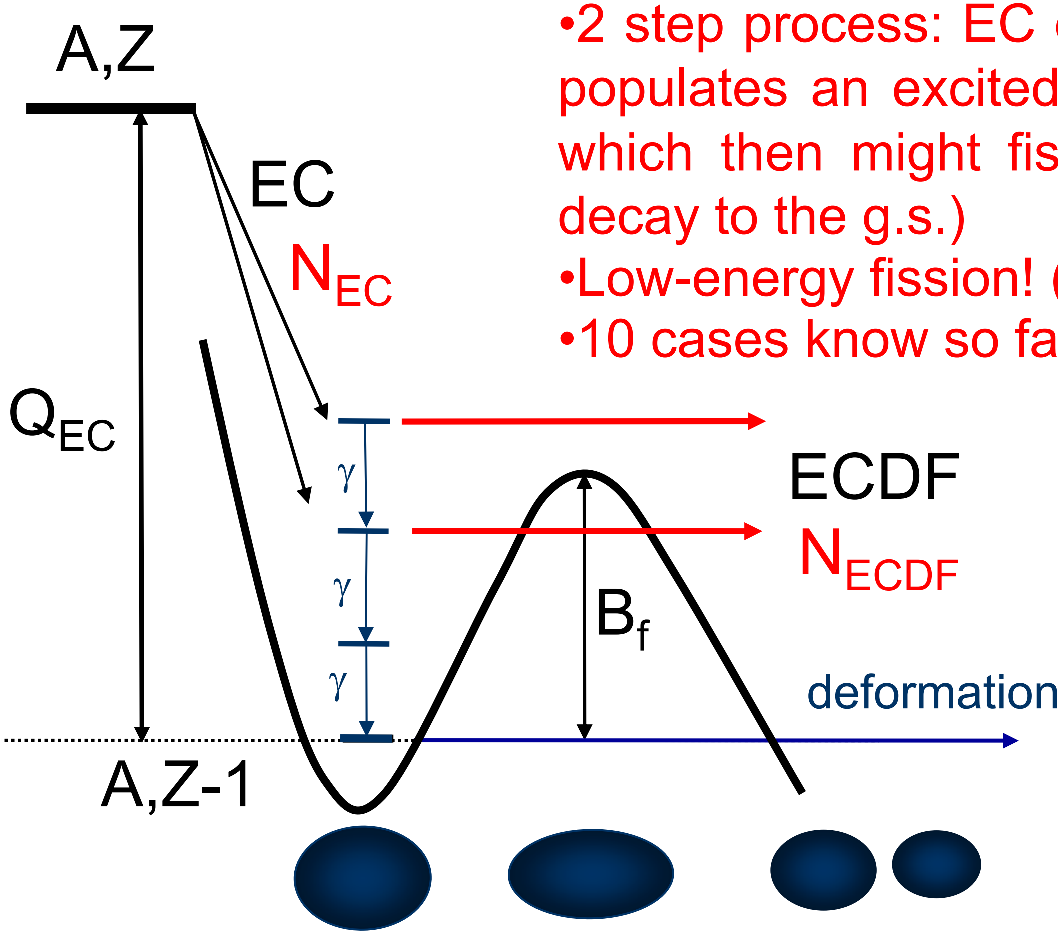
- Unfortunately, so exotic nuclei are not presently accessible by available techniques!

- That is why the underlying mechanisms and properties of beta-delayed fission (and of low-energy fission in general) have to be investigated by using alternative approaches and in other regions of the Nuclear Chart.

- According to semi-empirical estimates, the neutron-deficient nuclei in the U and Pb regions provide such a possibility via the ECDF decay

Electron-Capture Delayed Fission (ECDF, $T_{1/2}(ff)=T_{1/2}(EC)$)

Discovery: parent isotopes ^{232,234}Am(1966, Dubna)



- 2 step process: EC decay of a parent (A,Z) nucleus populates an excited state in the (A,Z-1) daughter, which then might fission (in competition with the γ decay to the g.s.)
- Low-energy fission! (E*~5-8 MeV)
- 10 cases know so far (neutron-def. Uranium region)

EC-delayed branch

$$P_{ECDF}=\frac{N_{ECDF}}{N_{EC}}$$

P_{ECDF} depends strongly on:

- Q_{EC} of the parent: the higher Q_{EC}, the larger the P_{ECDF}
- B_{fis} of the daughter: the lower B_{fis}, the larger the P_{ECDF}
- Actually, Q_{EC}-B_{fis} is important

ECDF Probability: Feeding Part

$$P_{ECDF} = \frac{N_{ECDF}}{N_{EC}} = \frac{\int_0^{Q_{EC}} (Q_{EC}-E)^2 \times S_\beta(E) \frac{\Gamma_f(E)}{\Gamma_{tot}(E)} dE}{\int_0^{Q_{EC}} (Q_{EC}-E)^2 \times S_\beta(E)\, dE}$$

$(Q_{EC}-E)^2$ – Phase factor for EC decay

$S_\beta(E)$ – β-strength function (nuclear matrix element)

For S_β calculations one can try:

- $S_\beta(E)$=Constant
- S_β ~ to the level density in the daughter
- Gross theory
- Microscopic approaches (e.g. QRPA)

ECDF Probability: Fission/gamma competition

$$P_{ECDF}=\frac{N_{ECDF}}{N_{EC}} \sim \frac{\int_0^{Q_{EC}} (Q_{EC}-E)^2 \times S_\beta(E) \times \frac{\Gamma_f(E,B_f)}{\Gamma_{tot}(E)} dE}{\int_0^{Q_{EC}} (Q_{EC}-E)^2 \times S_\beta(E)\, dE}$$

$$\frac{\Gamma_f}{\Gamma_{tot}}=\frac{\Gamma_f}{\Gamma_{f}+\Gamma_\gamma}$$ -ratio of the fission and total widths of excited levels in daughter (Γ_n is not important for neutron-deficient nuclei)

$$\Gamma_\gamma=\frac{9.7\times10^{-7}\times T^4\times \exp(E/T)}{2\pi\rho},$$ ρ – level density, T - temperature

$$\Gamma_f=\frac{1}{2\pi\rho}\left\{1+\exp\left[\frac{2\pi(B_f-E)}{h\omega_f}\right]\right\}^{-1}$$ -inverted parabola approximation

D.L. Hill and J.A.Wheeler

Measurement of P_{EDCF} allows to deduce Fission Barrier B_f

e.g . H.V. Klapdor et al., Z.Phys.A292, 1979,249; D. Habs et. al. Z.Phys. A285 (1978), 53

Low-Energy ECDF data ($^{232,234}Am$ as examples)

H. L. Hall et al., PRC42 (1990) 1480

- Fission barriers and their isospin dependence
- Energy distributions of fission fragments, thus TKE
- Mass distributions of fission fragments
- Gamma multiplicities for fission fragments
- Neutron multiplicities for fission fragments

ALL THIS FOR VERY EXOTIC NUCLEI WHICH DO NOT FISSION SPONTANEOSLY!

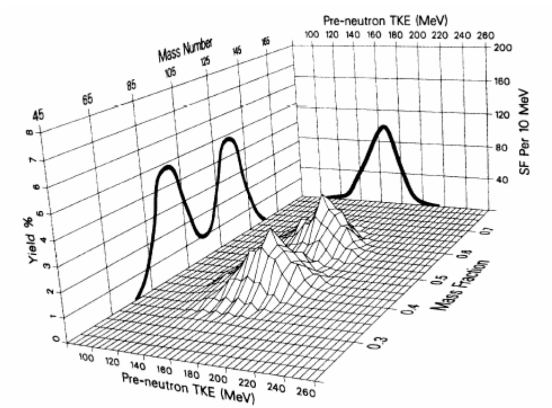


FIG. 2. Preneutron emission total-kinetic-energy (TKE) distribution of the ^{232}Am ϵDF mode and preneutron emission mass-yield distribution.

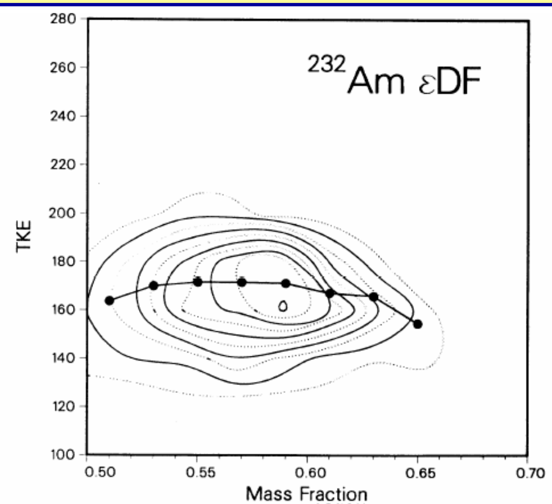
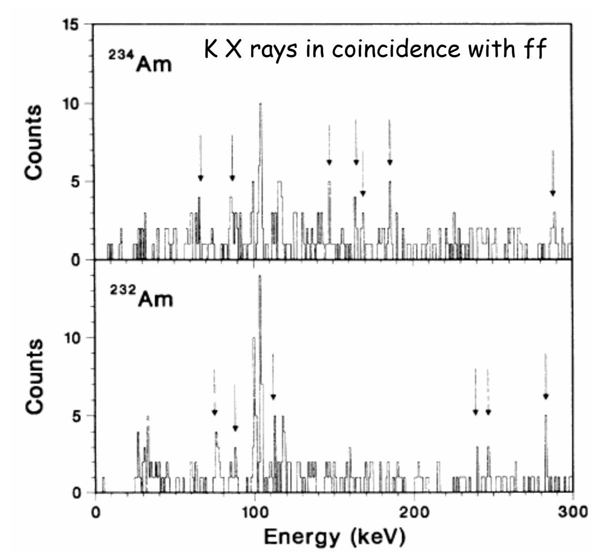
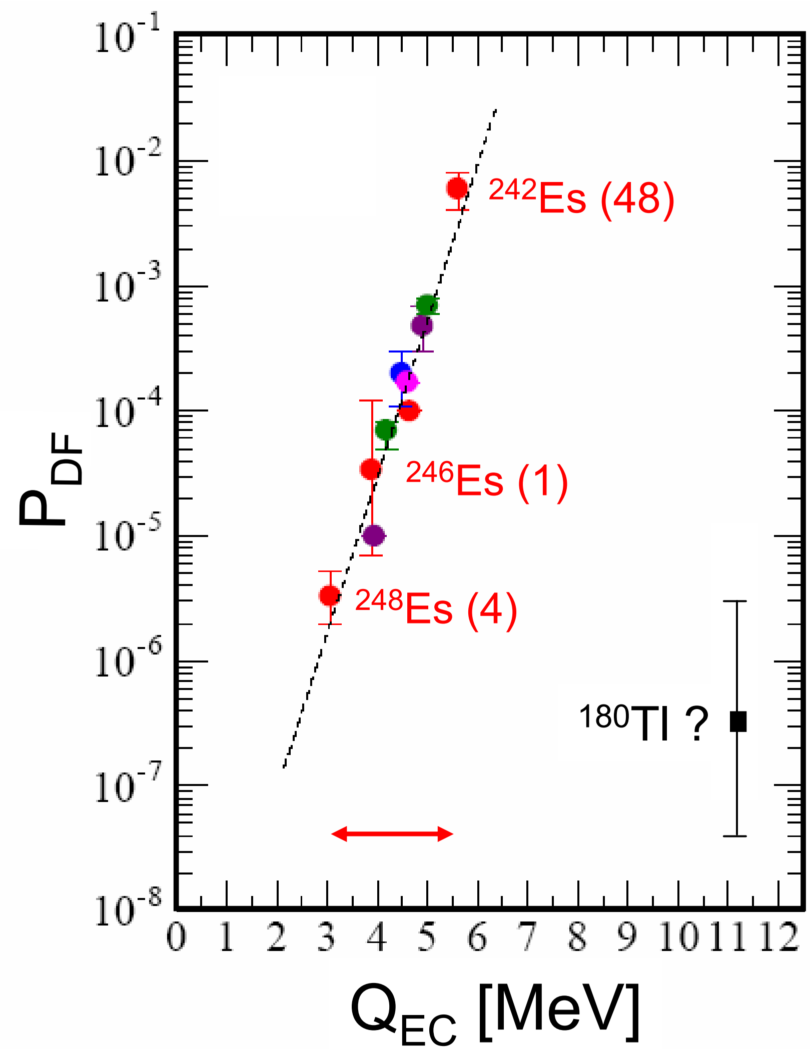


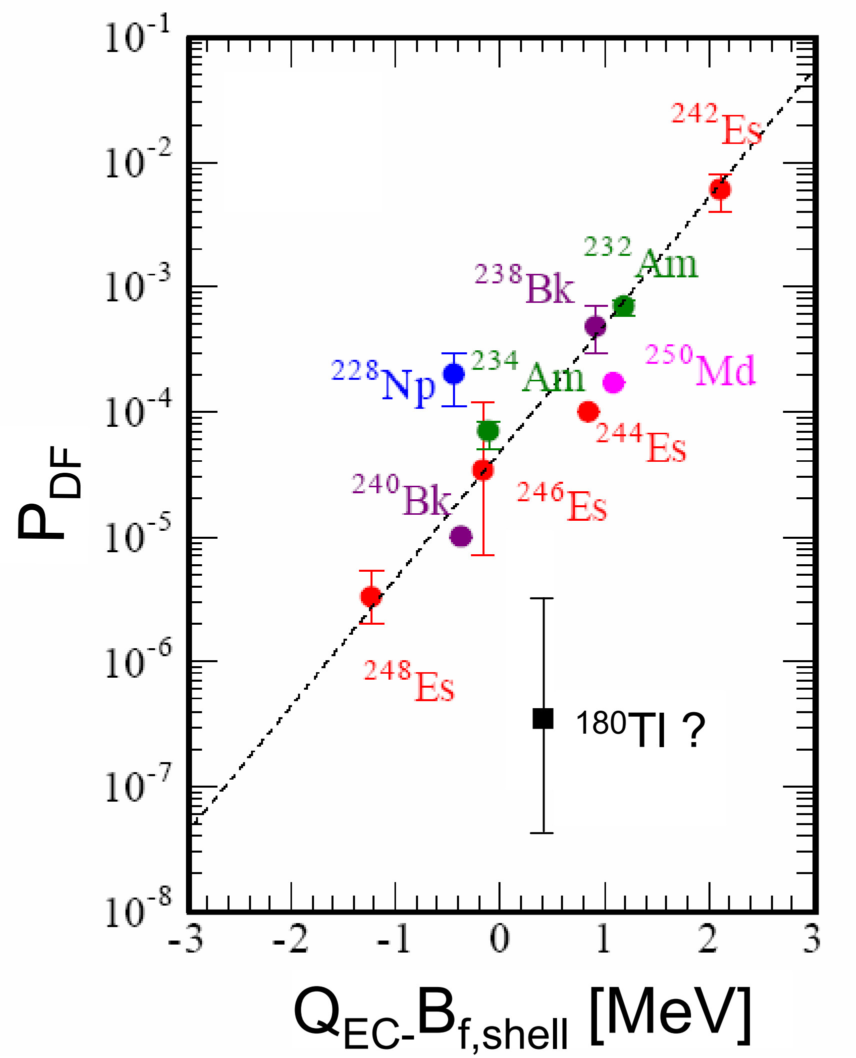
FIG. 4. Total kinetic energy and average total kinetic energy of ^{232}Am as a function of mass fraction. The solid points are average TKE values at each mass fraction. The contours represent the mass yield (normalized to 200%) as a function of TKE and mass fraction. The transition between a solid and dashed contour represents a change of 0.5% in the mass yield.



ECDF in trans-U region

- 10 known ECDF cases in trans-Uranium region (all odd-odd!)
- Relatively low Q_{EC} and B_f values (3-5 MeV)





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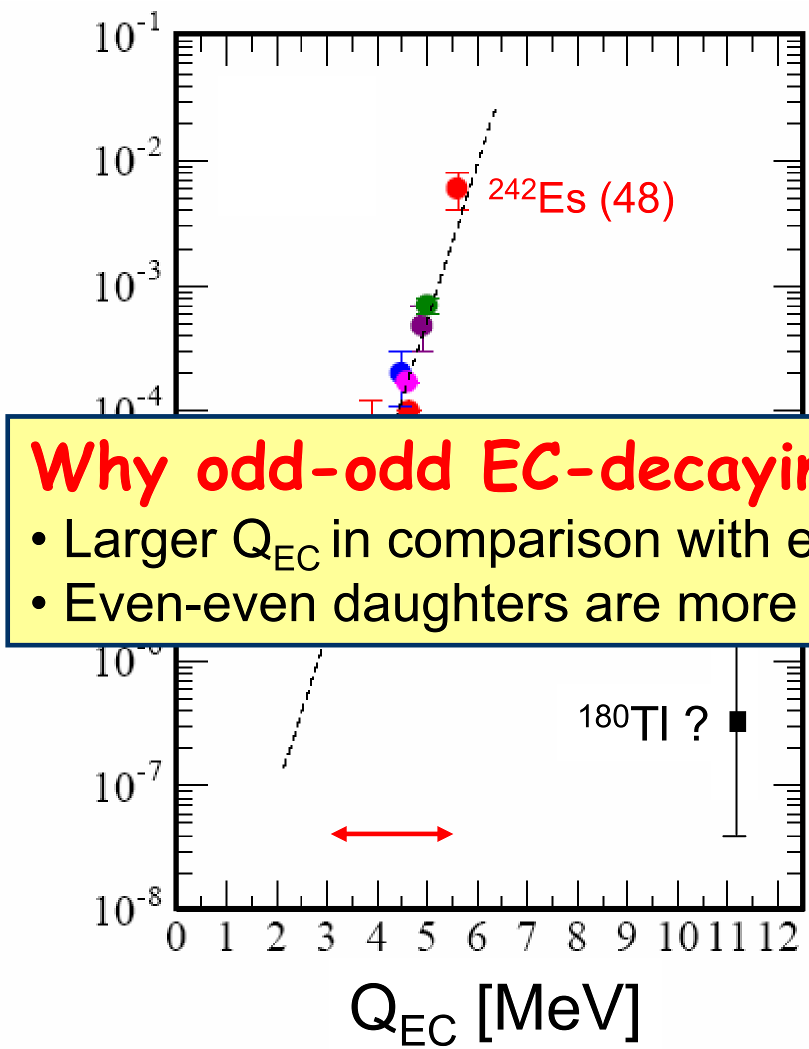
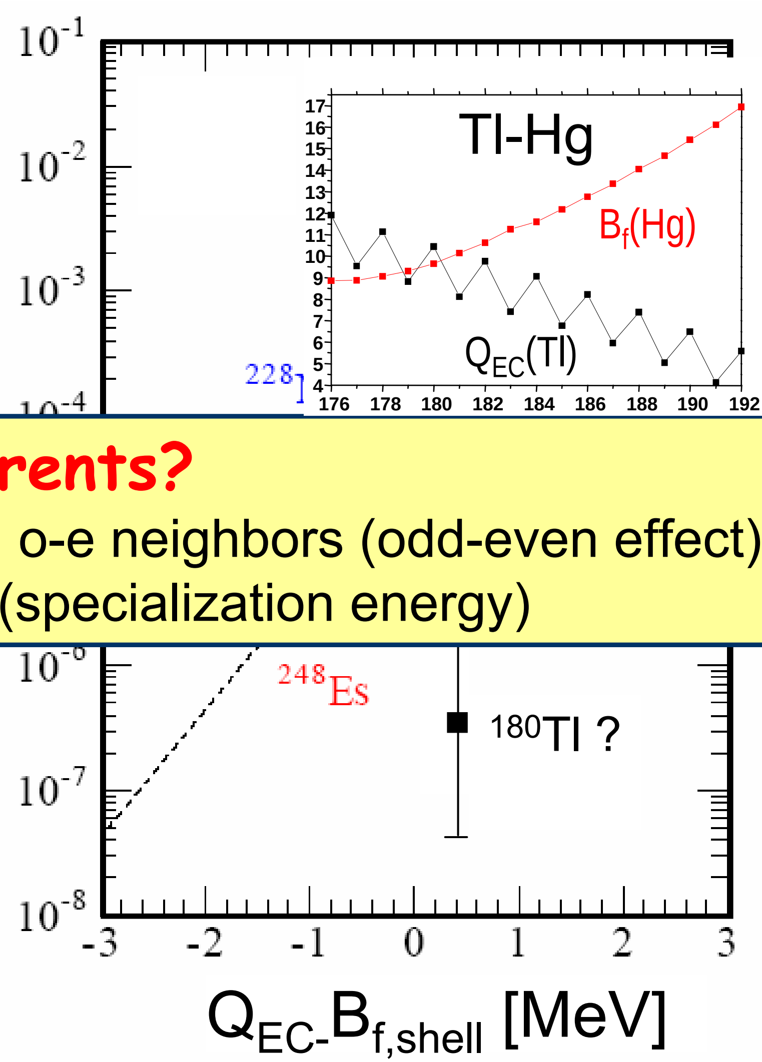


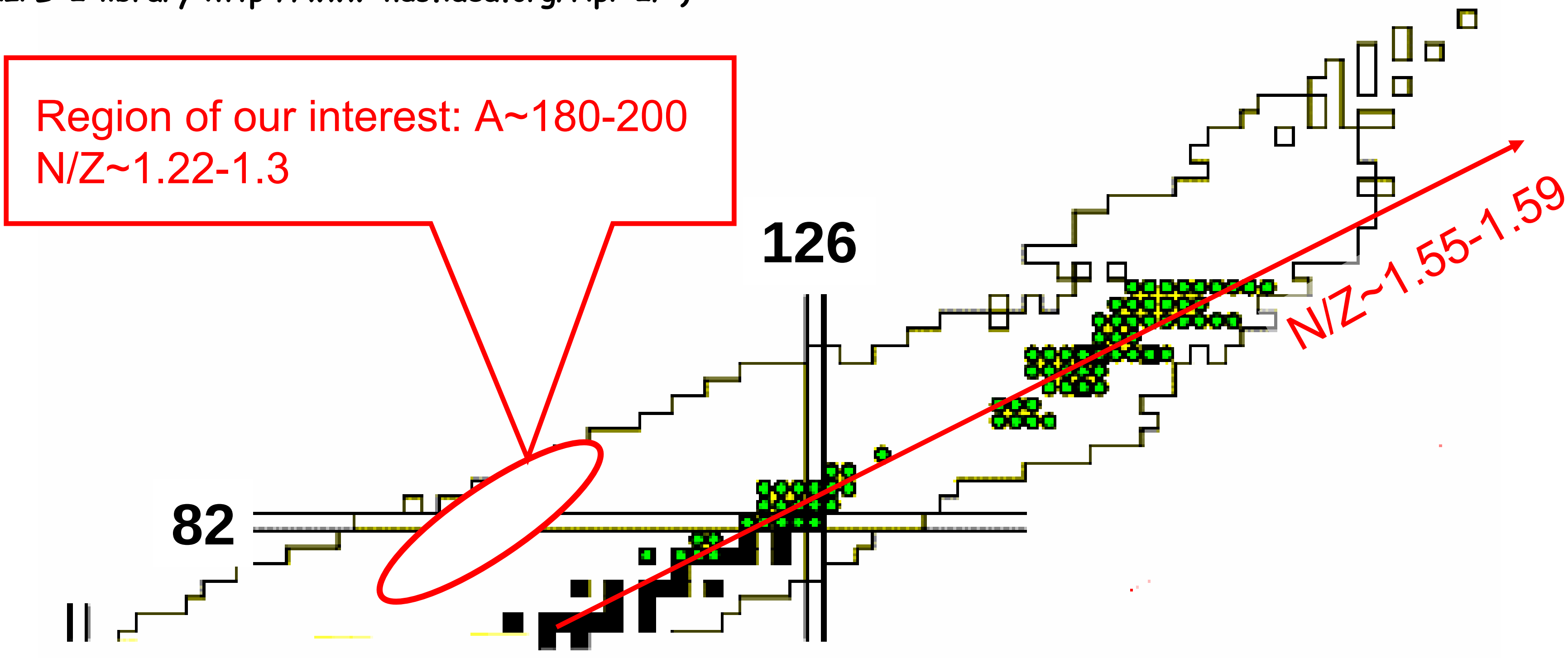


Why odd-odd EC-decaying parents?

- Larger Q_{EC} in comparison with e-e and o-e neighbors (odd-even effect)
- Even-even daughters are more fissile (specialization energy)

Region of our interest: Tl-Fr nuclei

Available data on fission barriers, Z ≥ 80
(RIPL-2 library http://www-nds.iaea.org/ripl-2/)

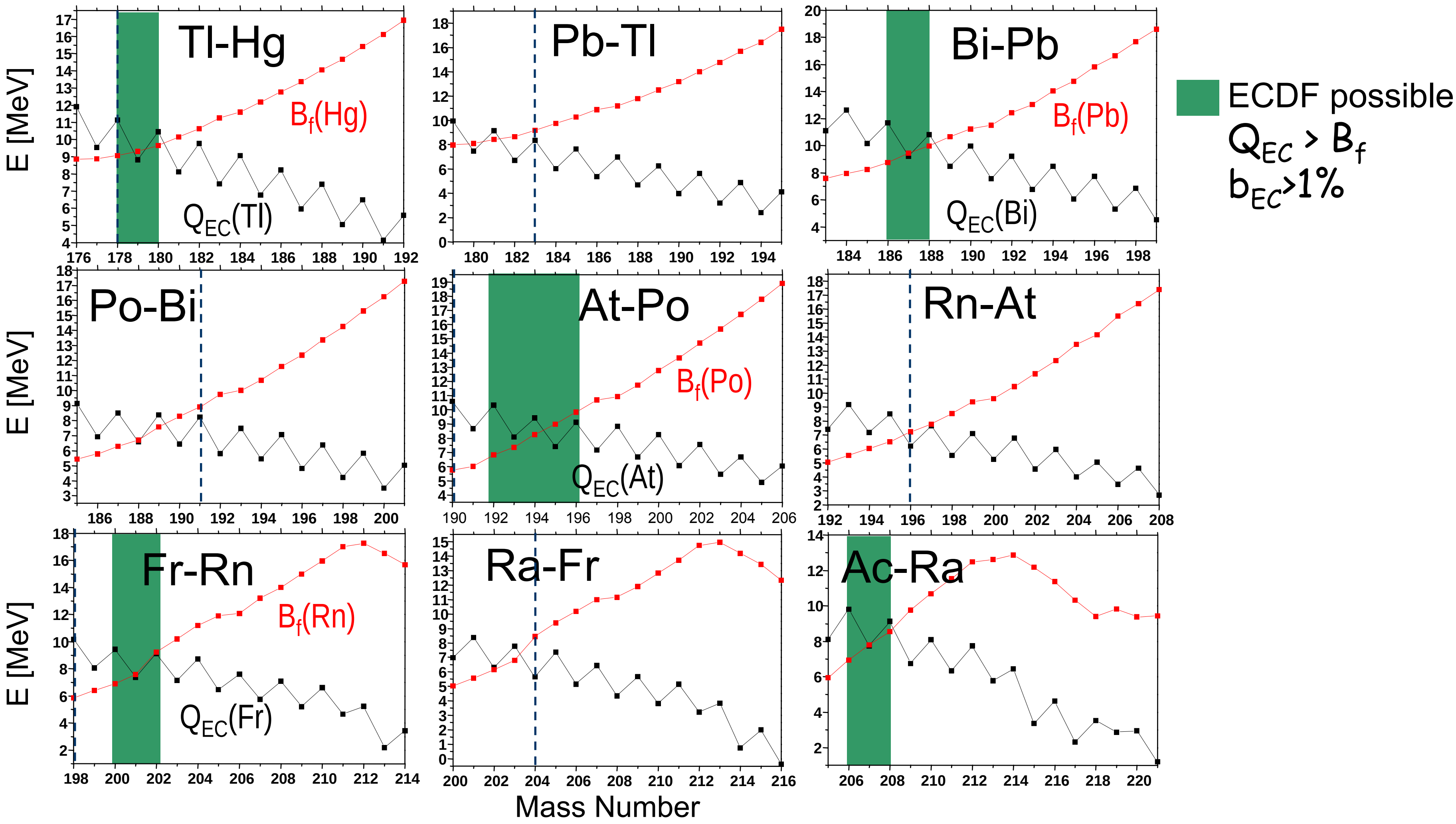


- ECDF gives access to nuclei with very exotic N/Z ratios: e.g. N/Z(^{180}Hg)=1.25

(⇒ unexpected mass/charge distributions?)

- Large Q_{EC} values (up to 11-12 MeV)

Q_{EC} vs B_f values in Pb region (look for cases $Q_{EC} > B_f$)

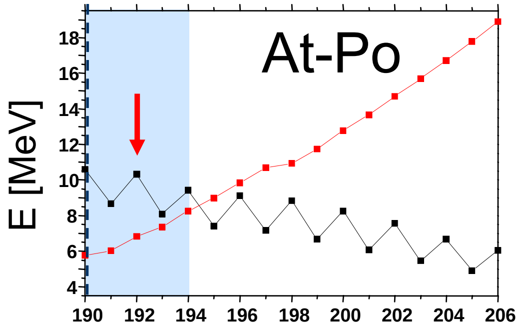


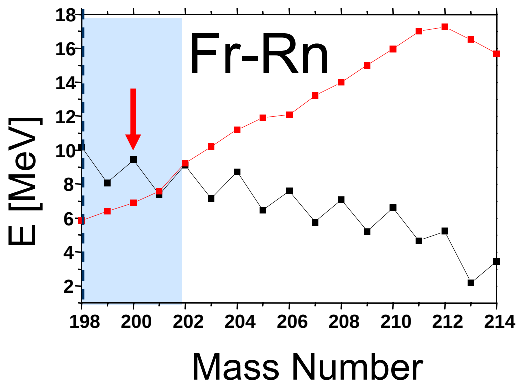
Red lines: Thomas-Fermi Fission Barriers, W.D. Myers, W. Swiatecki Phys. Rev. C60 (1999) 014606

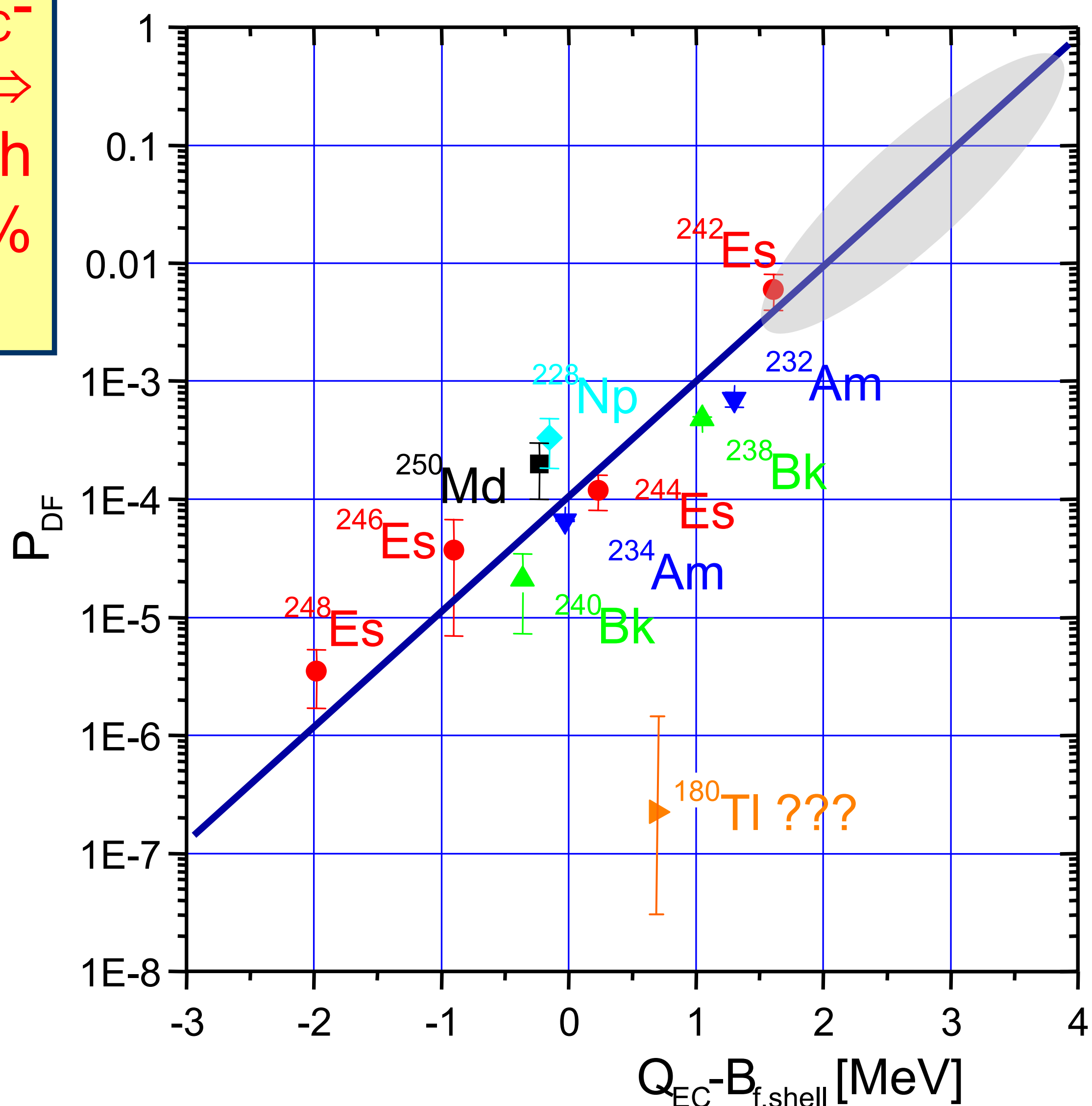
Black lines: Q_{EC}-values, P. Moller et al. At. Data and Nucl. Data table 59 (1995) 185

ECDF probability in the Pb region

Large Q_{EC} and Q_{EC}-B_f=3-4 MeV ⇒ Possibility to reach nuclei with 10-100% ECDF probability!



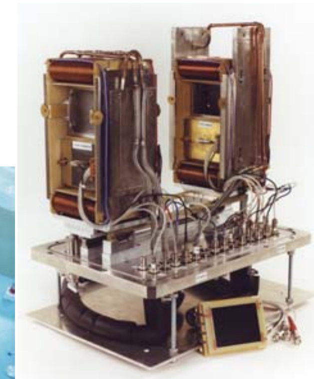


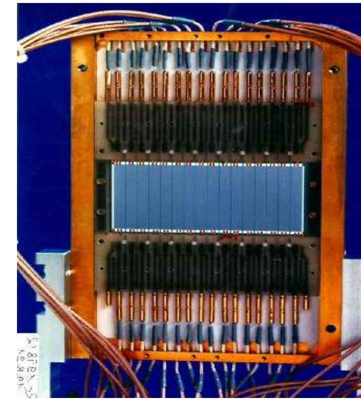


Velocity Filter SHIP (GSI, Darmstadt)

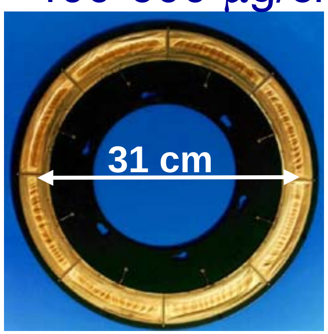
SHIP:

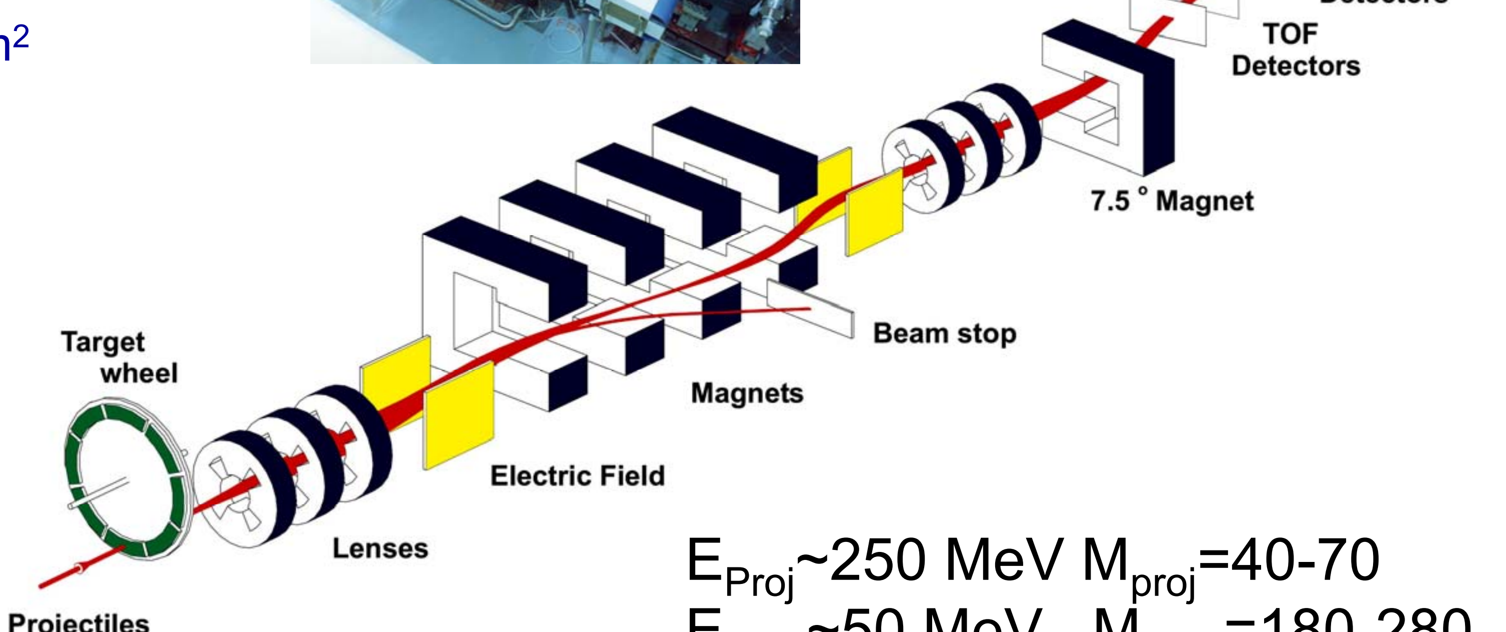
Separation time:	1 – 2 μs
Transmission:	20 – 50 %
Background:	10 – 50 Hz
Det. E. resolution:	18 – 25 keV
Det. Pos. resolution:	150 μm
Dead time:	3 – 25 μs





Rotating targets
~400-600 μg/cm²

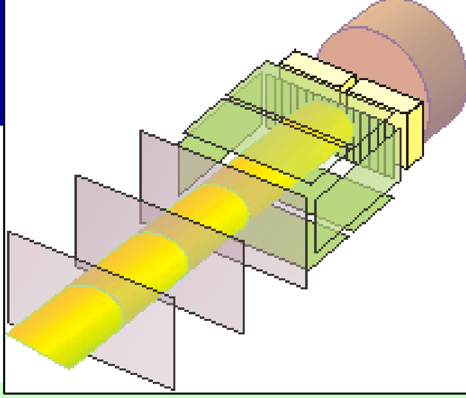




1 pμA of ^{52}Cr, ^{58}Ni
~6×10¹² pps

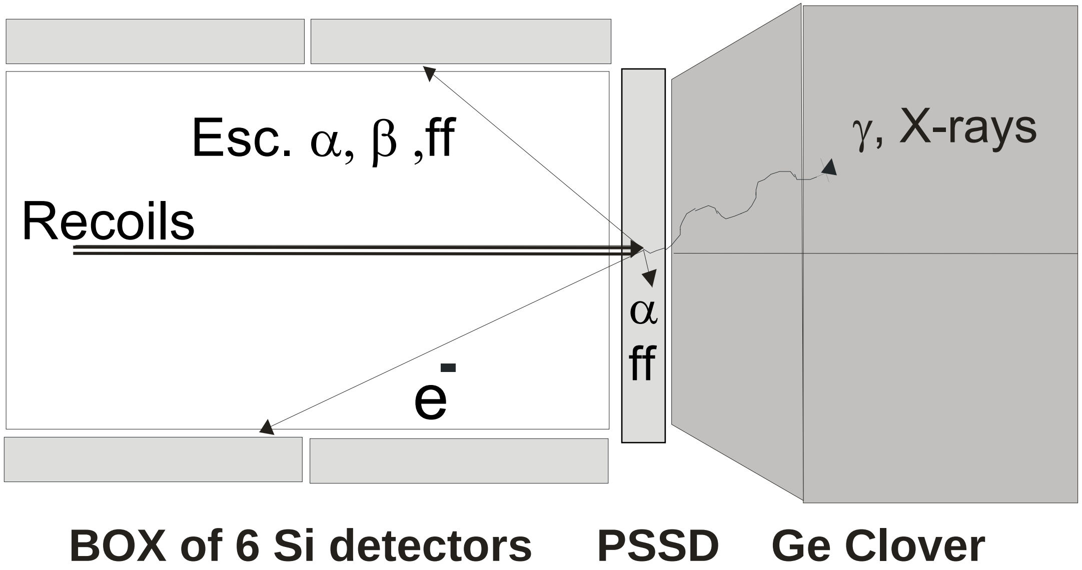
E_{Proj}~250 MeV M_{proj}=40-70
E_{EVR}~50 MeV M_{EVR}=180-280

SHIP Detection System



Measure **efficiently** all possible decays:

- particle decay (α, β, protons, fission) E=0.1-250 MeV
- gamma decay E=10-4000 keV
- internal conversion electrons E=50-500 keV

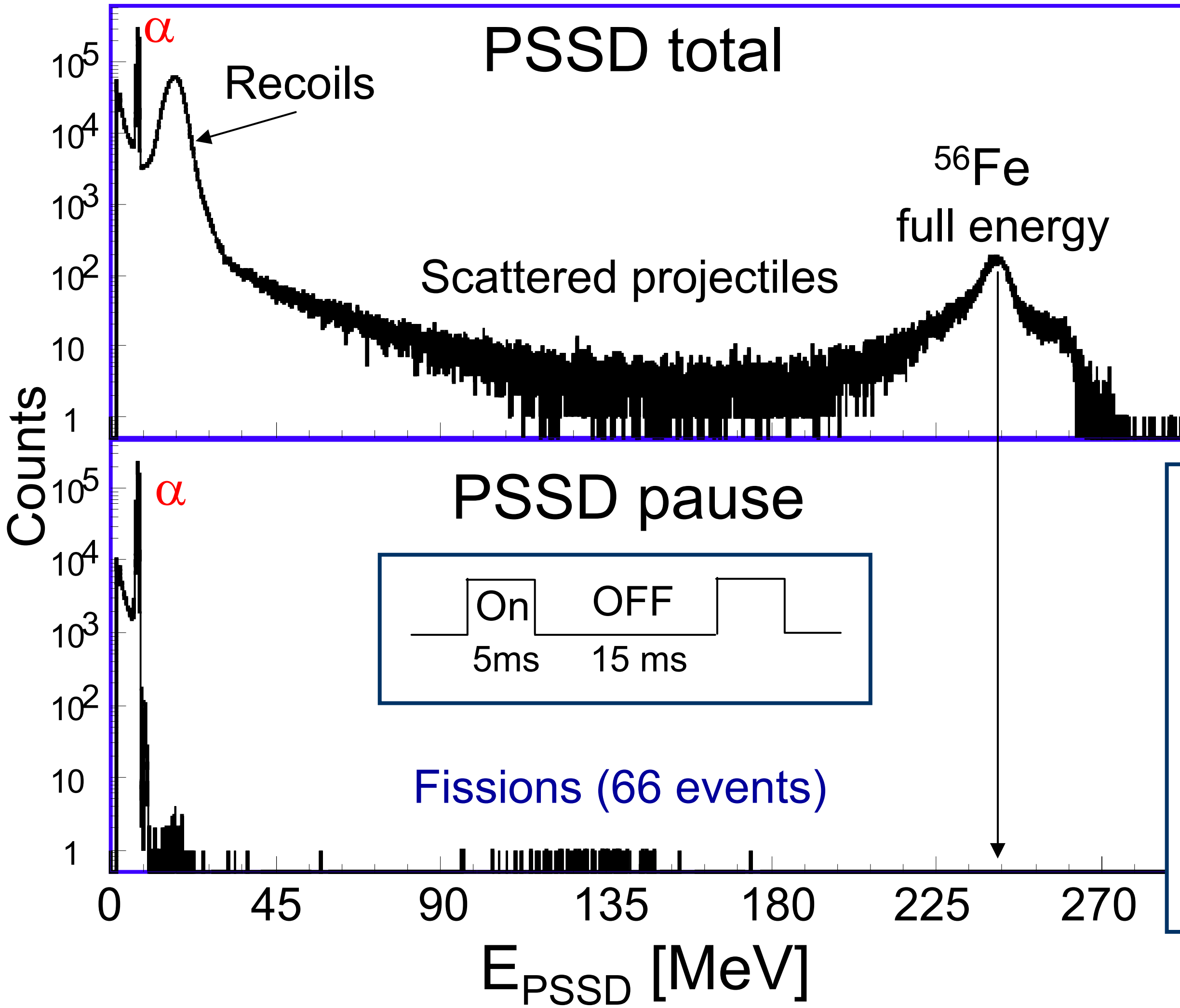


- **3 Time-Of-Flight detectors**
- **STOP detector** – 16 position sensitive Si strips (35×80mm), pos. resolution FWHM=150 μm, energy resolution 14 keV
- **6 BOX Si detectors** – for β and escaping α particles with a solid angle 80% of 2π
- **GAMMA detectors** – large-volume Clover detector for x rays or γ rays in coincidence with α's
- **VETO detector** – reduces background

A.N. Andreyev et al. 'Conversion electron and β decay spectroscopy at SHIP', NIM A533, 416 (2004)

Unambiguous identification of ECDF in ^{194}At, SHIP(GSI)

A.Andreyev et al, paper in preparation



$^{56}Fe+^{141}Pr \rightarrow ^{194}At+3n$

$I(^{56}Fe)$~600 pnA

86×10^3 nuclei

66 fission events (pause)

Identification based on:

- Half-life
  - $T_{1/2,\alpha}(^{194}At)=280(20)$ ms
  - $T_{1/2,fiss}(^{194}At)=300(60)$ ms
- Excitation functions
- Cross-irradiation (^{56}Fe,^{52}Cr)
- Double fold ff events (BOX)
- Coincidences with gammas

First observed in the $^{52}Cr+^{144}Sm \rightarrow ^{194}At+pn$ reaction (SHIP,2006)

16 fissions in pause

Unambiguous identification of ECDF in ^{194}At, SHIP(GSI)

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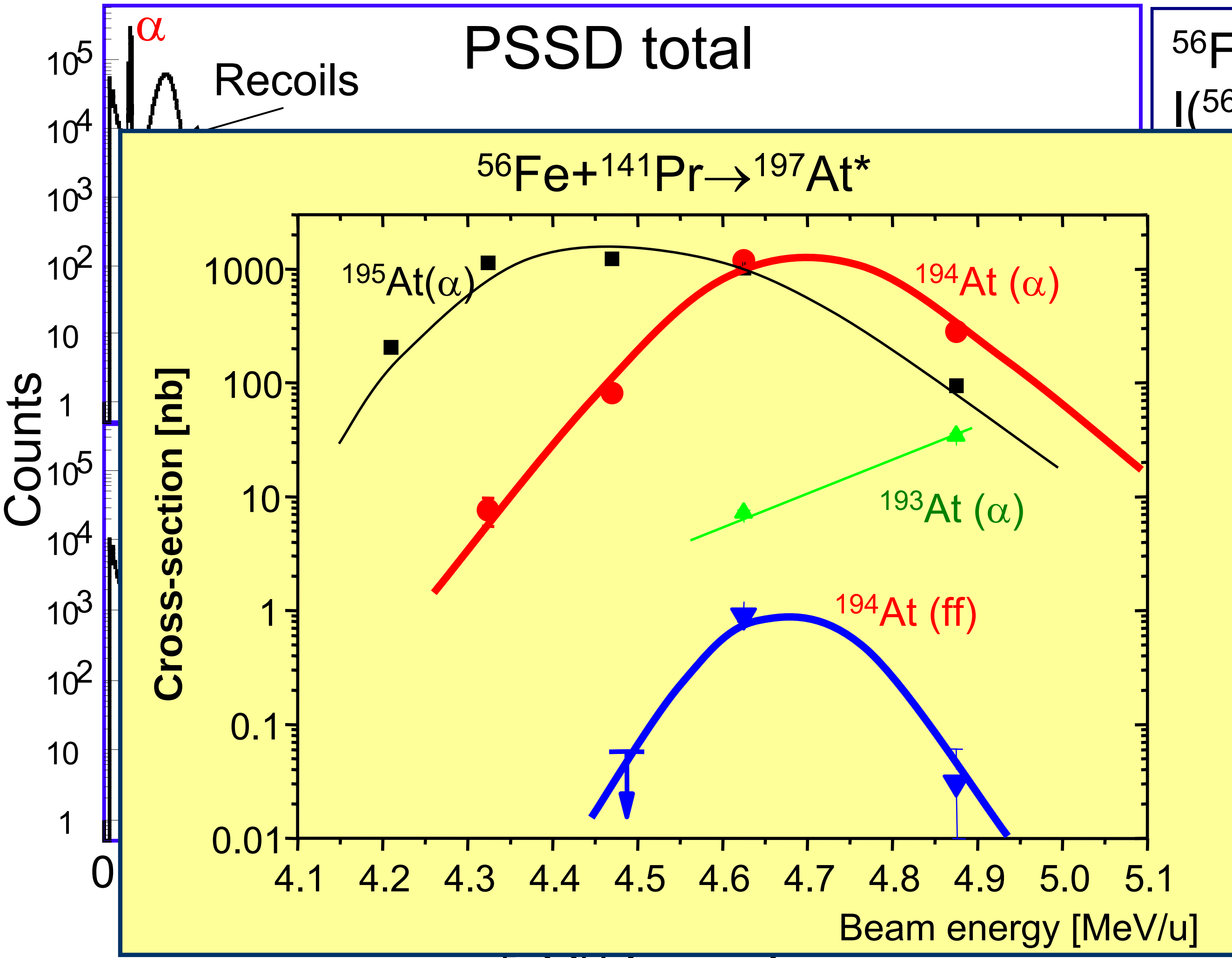

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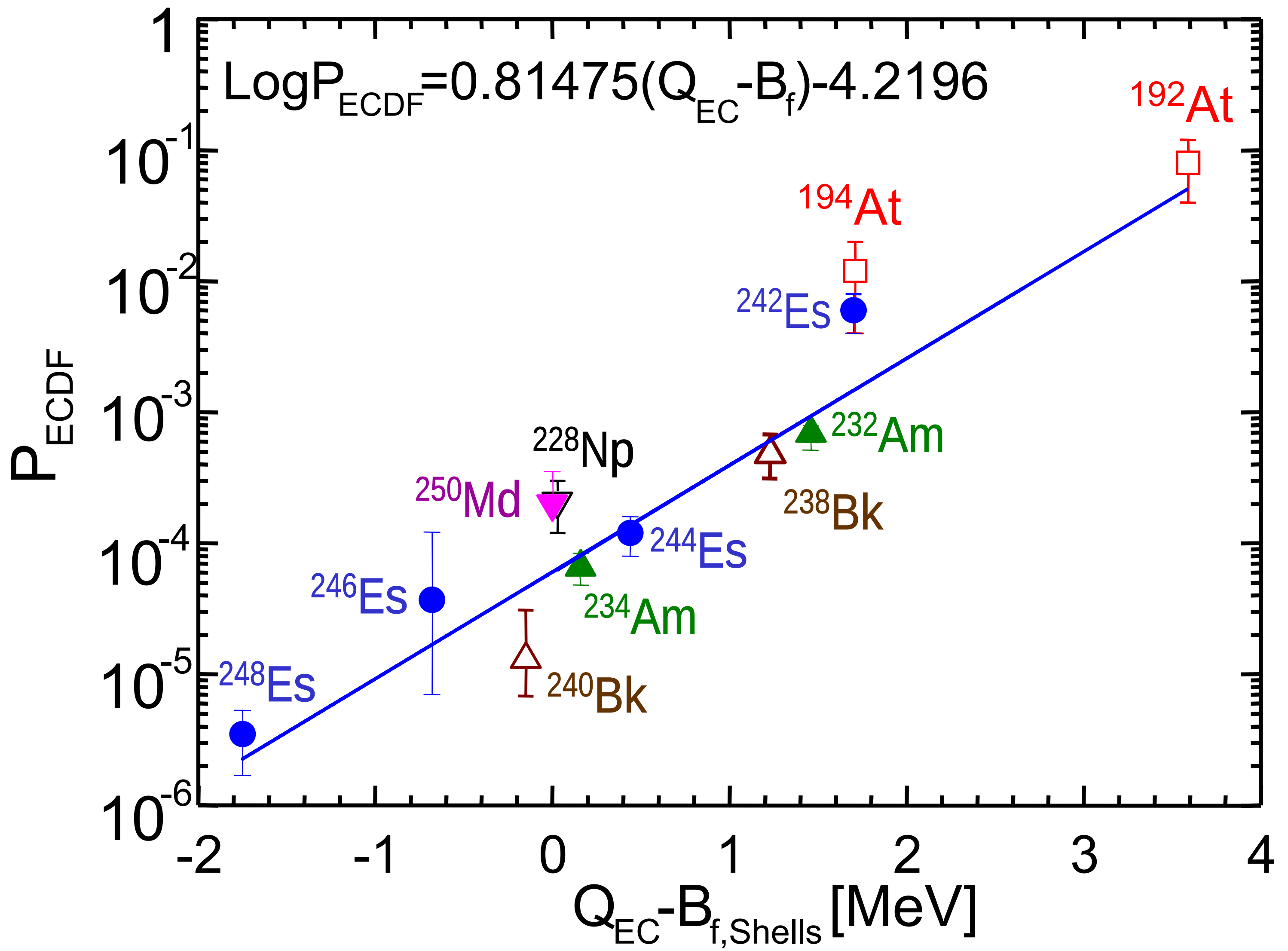
First observed in the $^{52}Cr + ^{144}Sm \rightarrow ^{194}At$+pn reaction (SHIP,2006)

16 fissions in pause

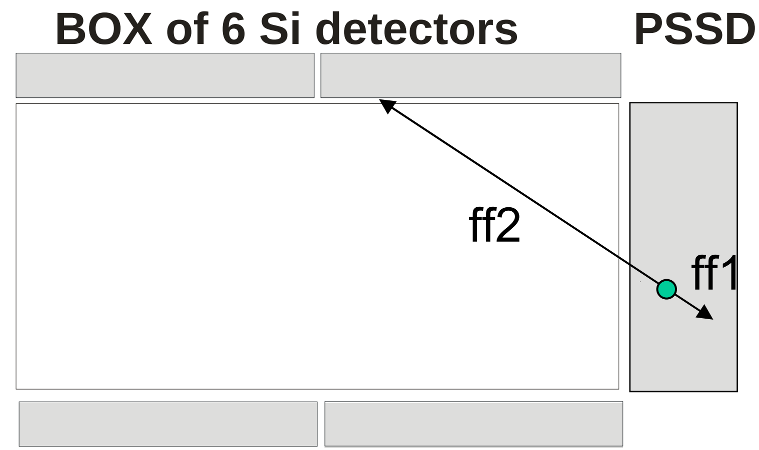
P_{ECDF} for $^{192,194}At$ (Preliminary!)

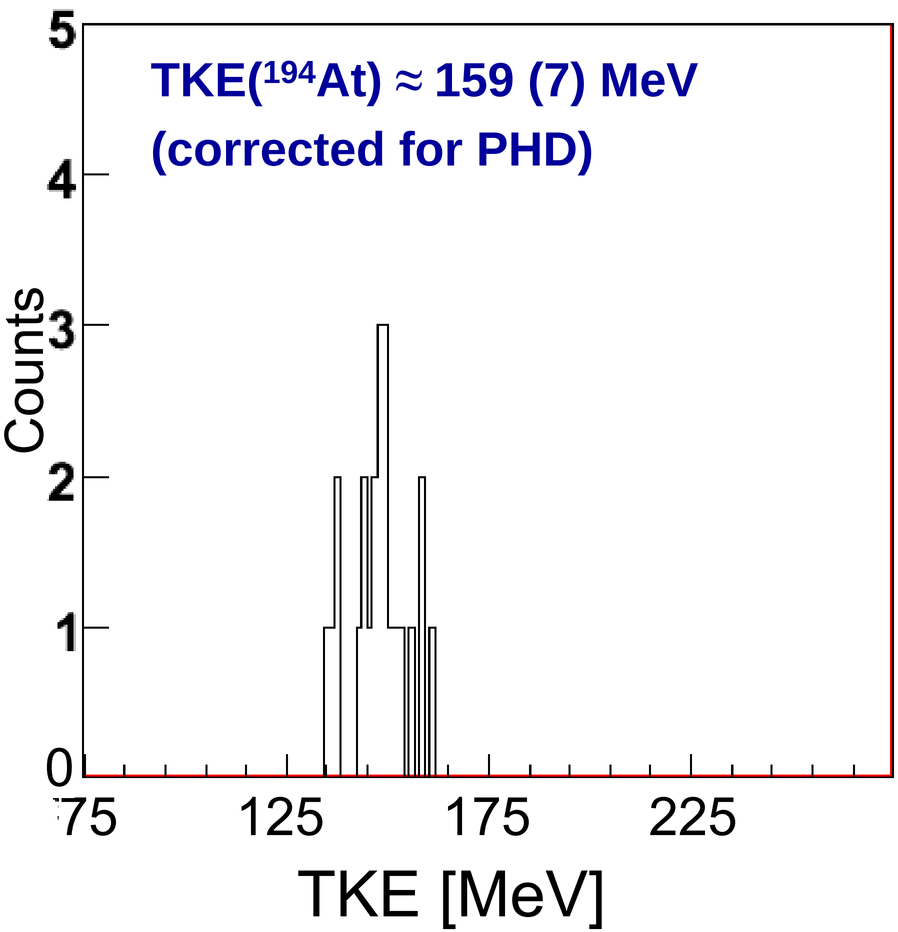


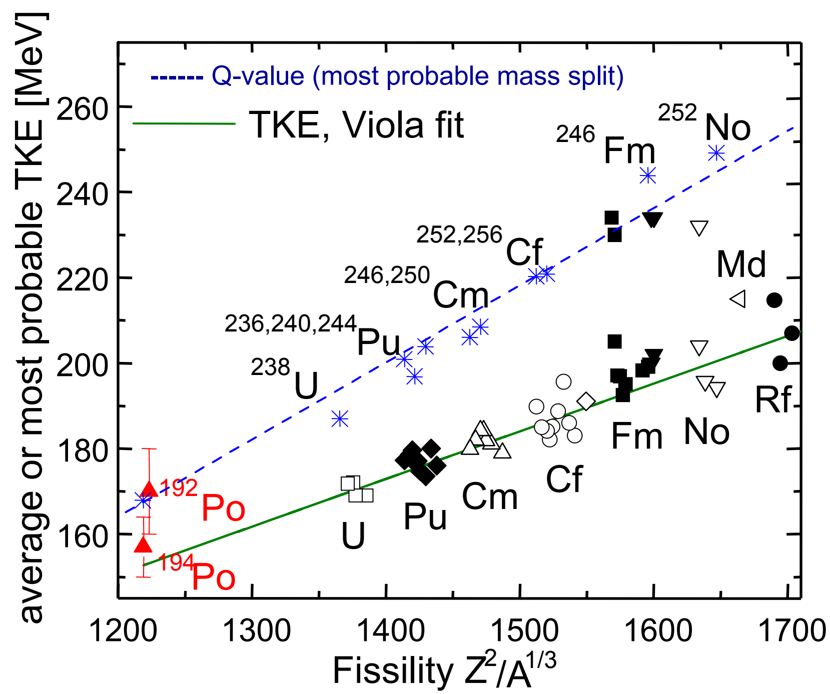
Q_{EC} and B_f values are from the TF model

Total Kinetic Energy in the EC-delayed fission of ^{194}At

TKE: Add up the energies of 2ff from the PSSD and BOX detectors







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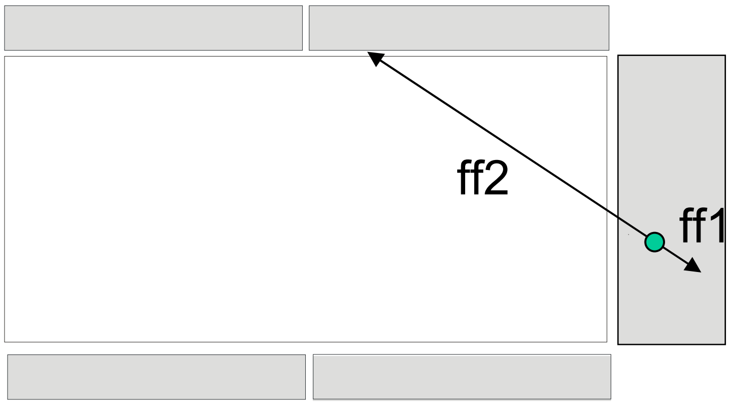


^{252}Cf(sf):

Q[^{252}Cf-(^{142}Ba+^{110}Mo)]=219 MeV

<TKE>=185 MeV

Δ(Q-TKE)=34 MeV

^{194}Po(ECDF):

Q[^{194}Po – (^{98}Mo+^{96}Mo)]=166 MeV

<TKE>=157(7) MeV

Δ(Q-TKE)=9(7) MeV (+E* after EC)

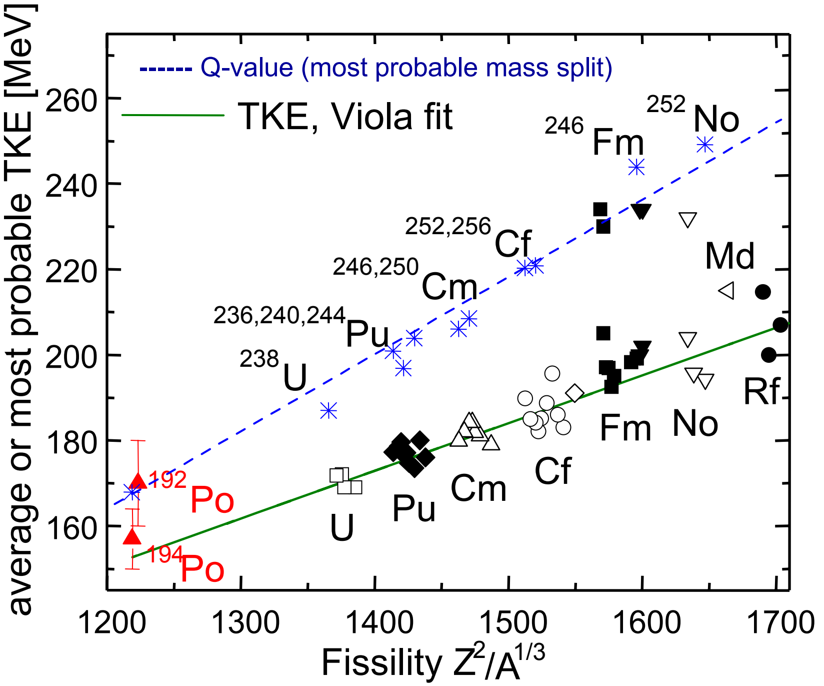
^{192}Po(ECDF):

Q[^{192}Po – (^{96}Mo+^{96}Mo)]=165 MeV

<TKE>=170(10) MeV

Δ(Q-TKE)= - 5(10) MeV (+E* after EC)

Cold fission of $^{192,194}Po$? (no neutron emission during fission!)

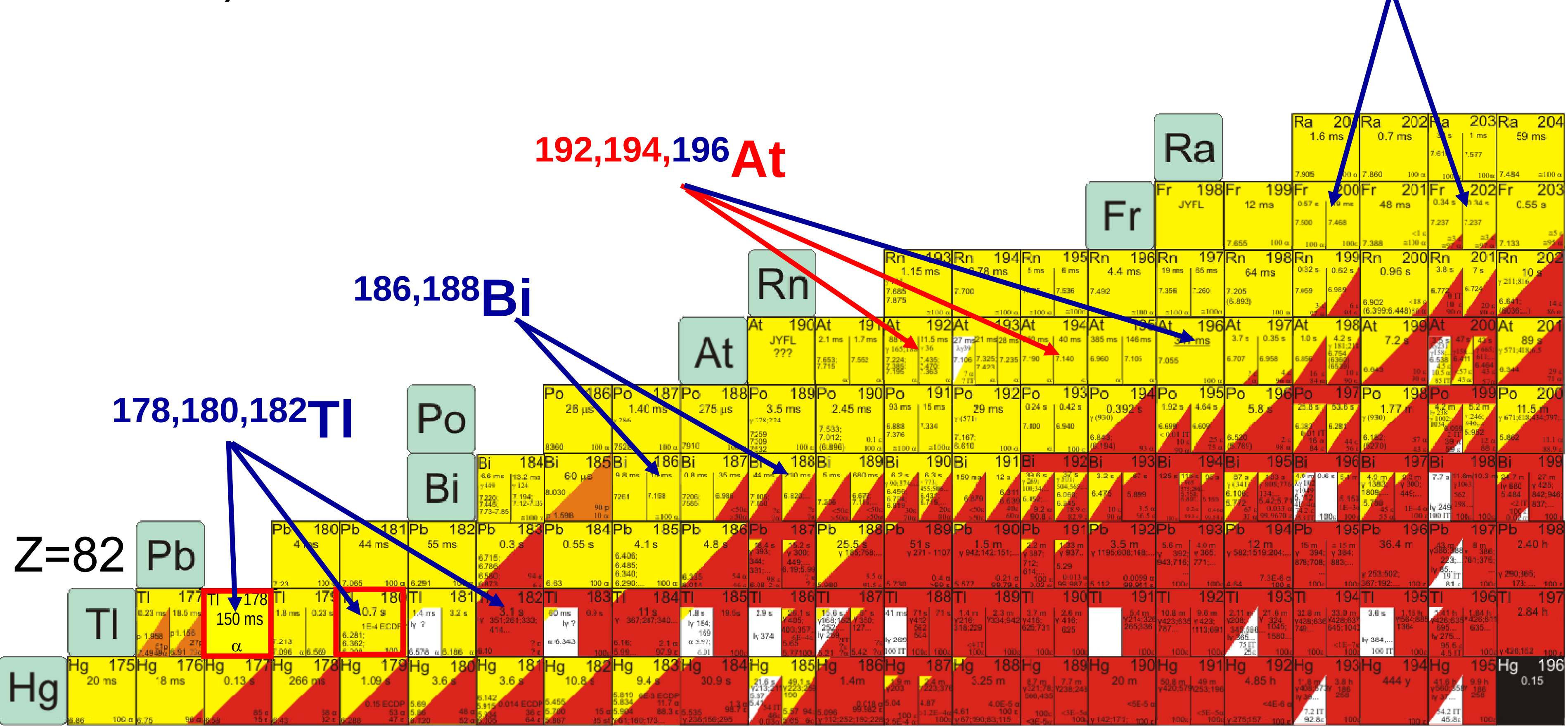


Current and future ECDF studies in the Pb region

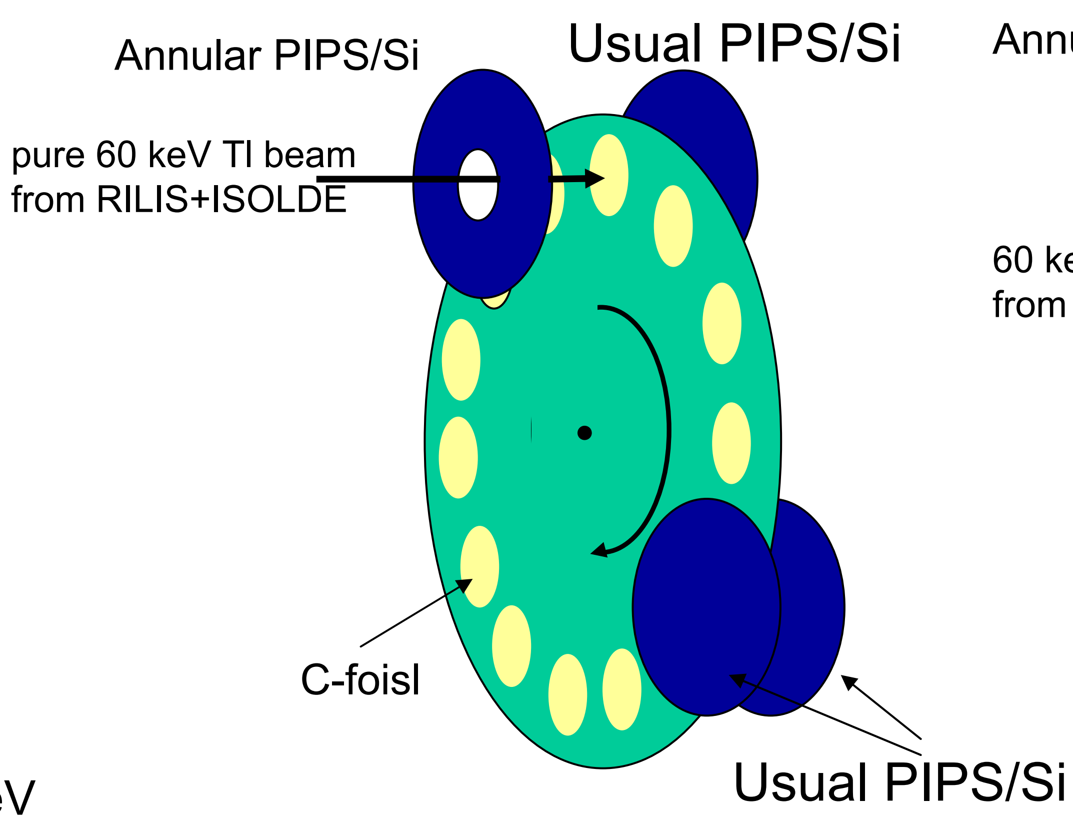
Identification of new ECDF nuclei and detailed studies (e.g. B_f values, TKE…) of:

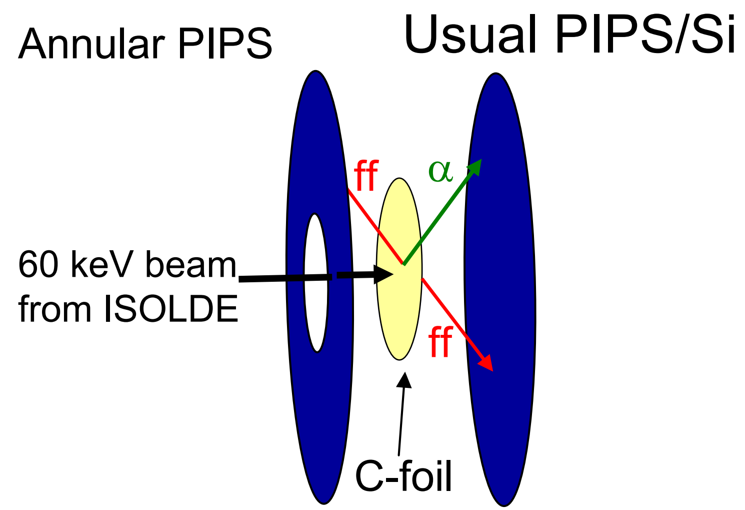
- **^{178,180,182}Tl – approved experiment at ISOLDE**
- **^{186,188}Bi – SHIP**
- **^{200,202}Fr, ^{192}At ….**

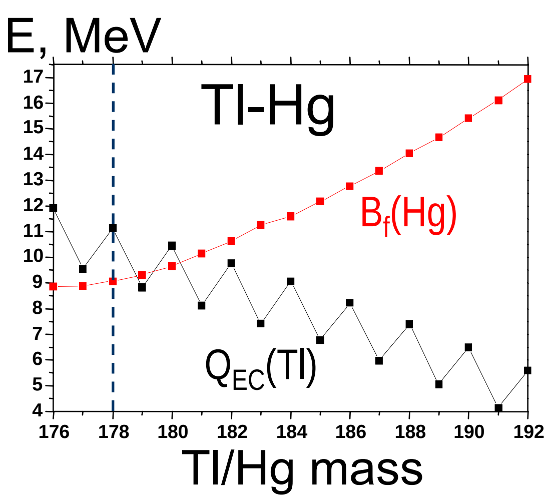
200,202Fr



ECDF of ^{178,180,182}Tl isotopes at ISOLDE (to be run in 2008)





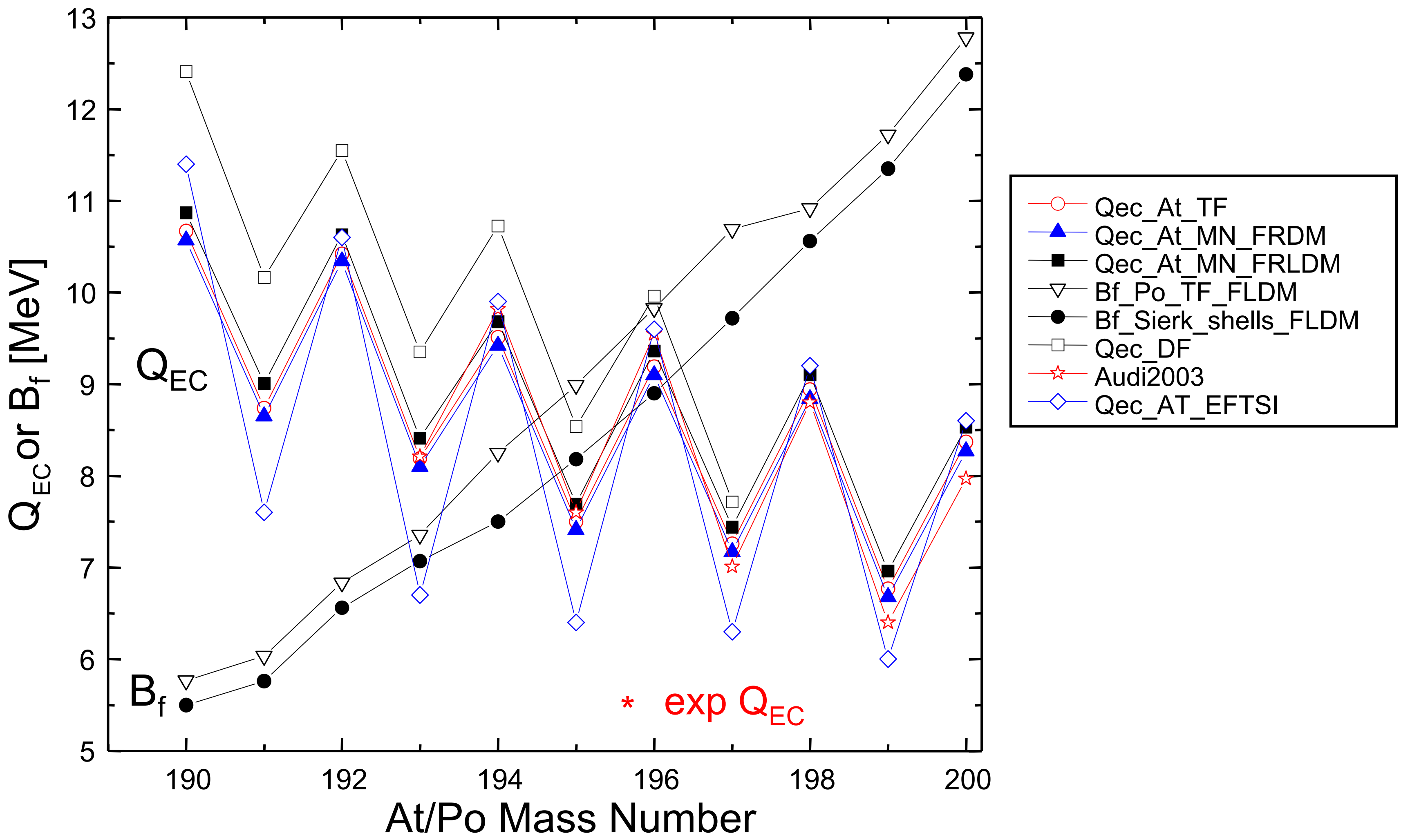


Setup: PIPS/Si detectors from both sides of the C-foil

- Simple setup & DAQ: 4 PIPS (1 of them – annular)
- Large geometrical efficiency (up to 80%)
- 2 fold fission fragment coincidences
- ff-gamma coincidences

Thank you!

Q_{EC}(At) and B_f(Po) in different models



(Speculations?) Double-Magic Fission?

One of the goals of ISOLDE proposal is ECDF of ^{178}Tl

How its daughter ^{178}Hg(N/Z=1.225) would fission?

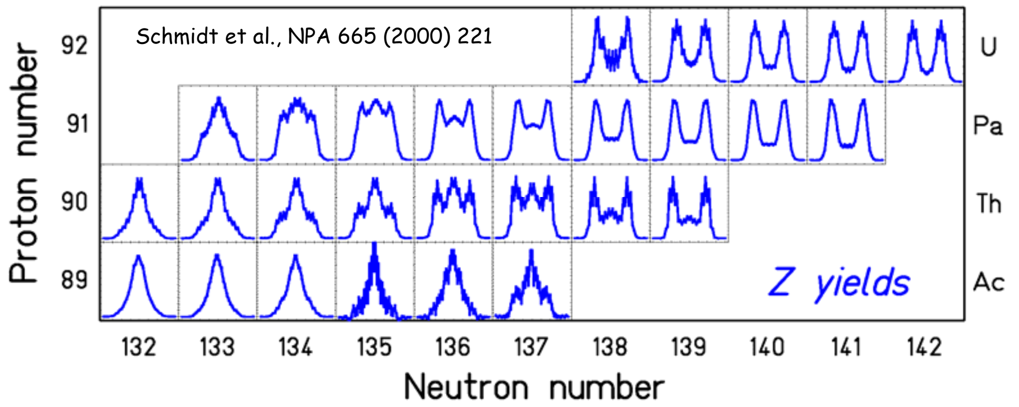
Would it give ‘double-magic’ fission – two double-magic ff’s?

very neutron-rich ^{78}Ni (Z=28,N=50 N/Z=1.79)

very neutron-deficient ^{100}Sn (Z=50,N=50 N/Z=1)

P. Moller (private communication): Most probably – NOT as a main channel

- Most probable mass splits ~90/~90 (^{90}Zr/^{90}Zr N/Z=1.25)
- but what about very asymmetical split at the wings? :

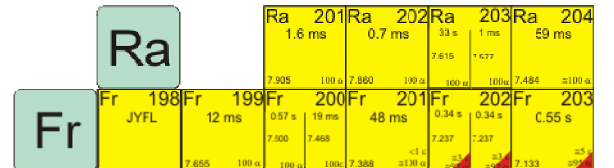


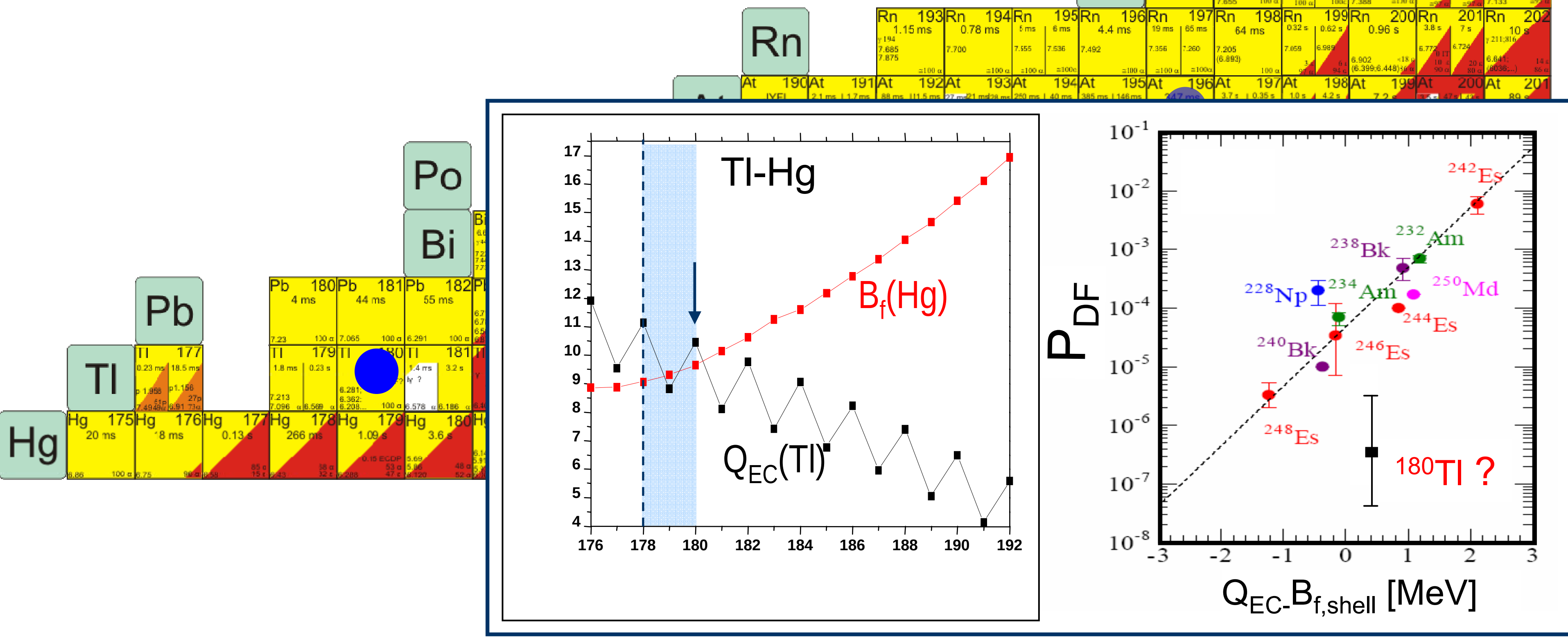
Previous Studies in the Pb region (Dubna)

Yu. A. Lazarev et al. Europhys. Lett. 4 (1987) 893; and Inst. Phys. Conf. Ser. No132 (1992) 739

"Most probable" candidates: ^{180}Tl ($P_{ECDF}=3\times10^{-(7\pm1)}$), ^{188}Bi, ^{196}At (no P_{ECDF} data)

- Irradiations inside the cyclotron (no A,Z selection for products)
- Rotating wheel system, thick effective targets (2 mg/cm^2)
- Cross-irradiations, apparent σ_{fis}~15-50 pb
- Mica detectors (fission tracks only)
- Never confirmed (not in the Tables)
- No continuation with these studies so far



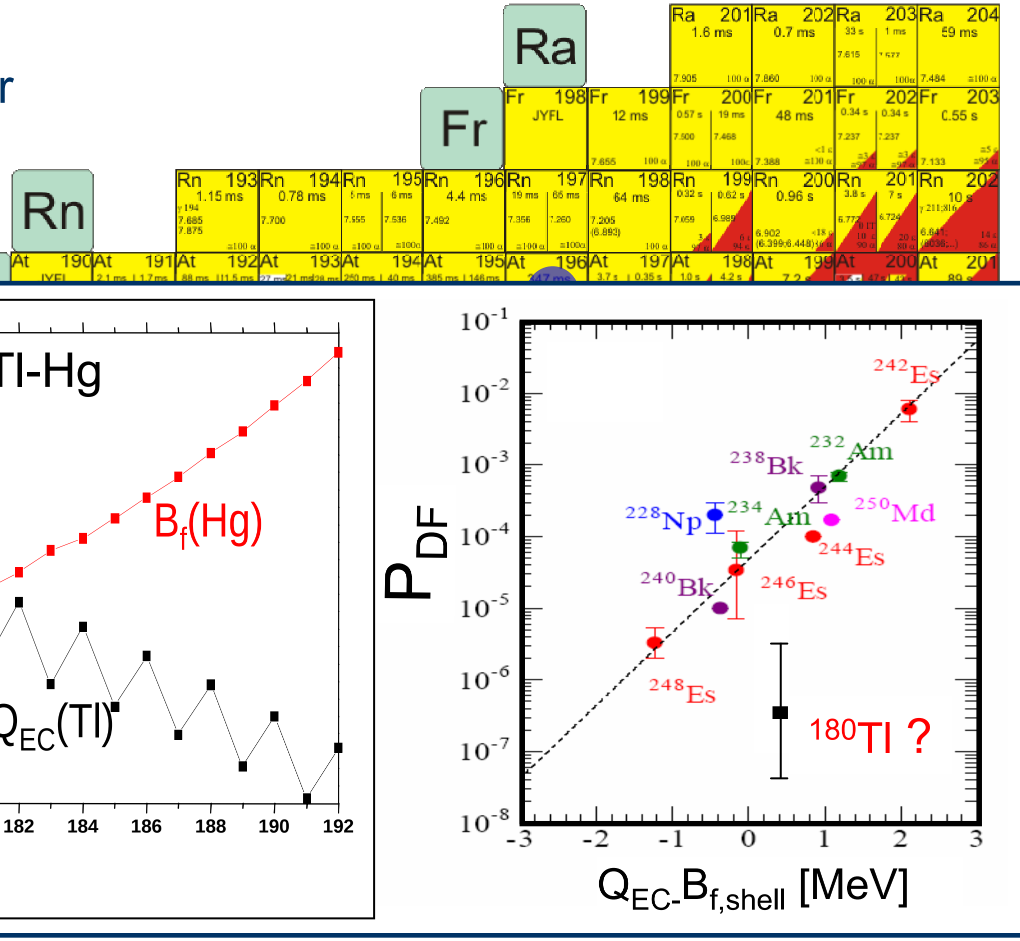


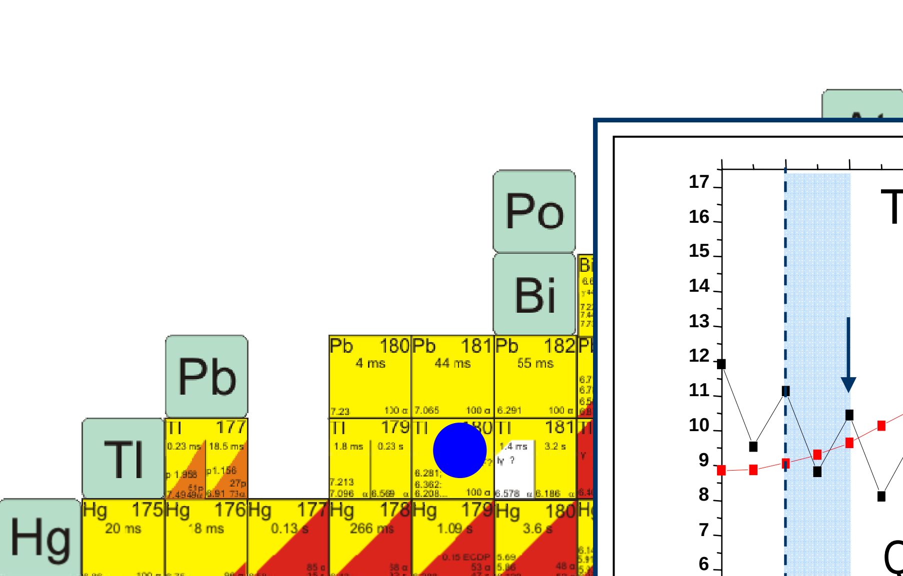
Previous Studies in the Pb region (Dubna)

Yu. A. Lazarev et al. Europhys. Lett. 4 (1987) 893; and Inst. Phys. Conf. Ser. No132 (1992) 739

"Most probable" candidates: ^{180}Tl ($P_{ECDF}=3\times10^{-(7\pm1)}$), ^{188}Bi, ^{196}At (no P_{ECDF} data)

- Irradiations inside the cyclotron (no A,Z selection for products)
- Rotating wheel system, thick effective targets (2 mg/cm^2)
- Cross-irradiations, apparent σ_{fis}~15-50 pb
- Mica detectors (fission tracks only)
- Never confirmed (not in the Tables)
- No continuation with these studies so far





An example: Fission Barrier of ^{232}Pu

D. Habs et. al. Z.Phys. A285 (1978), 53

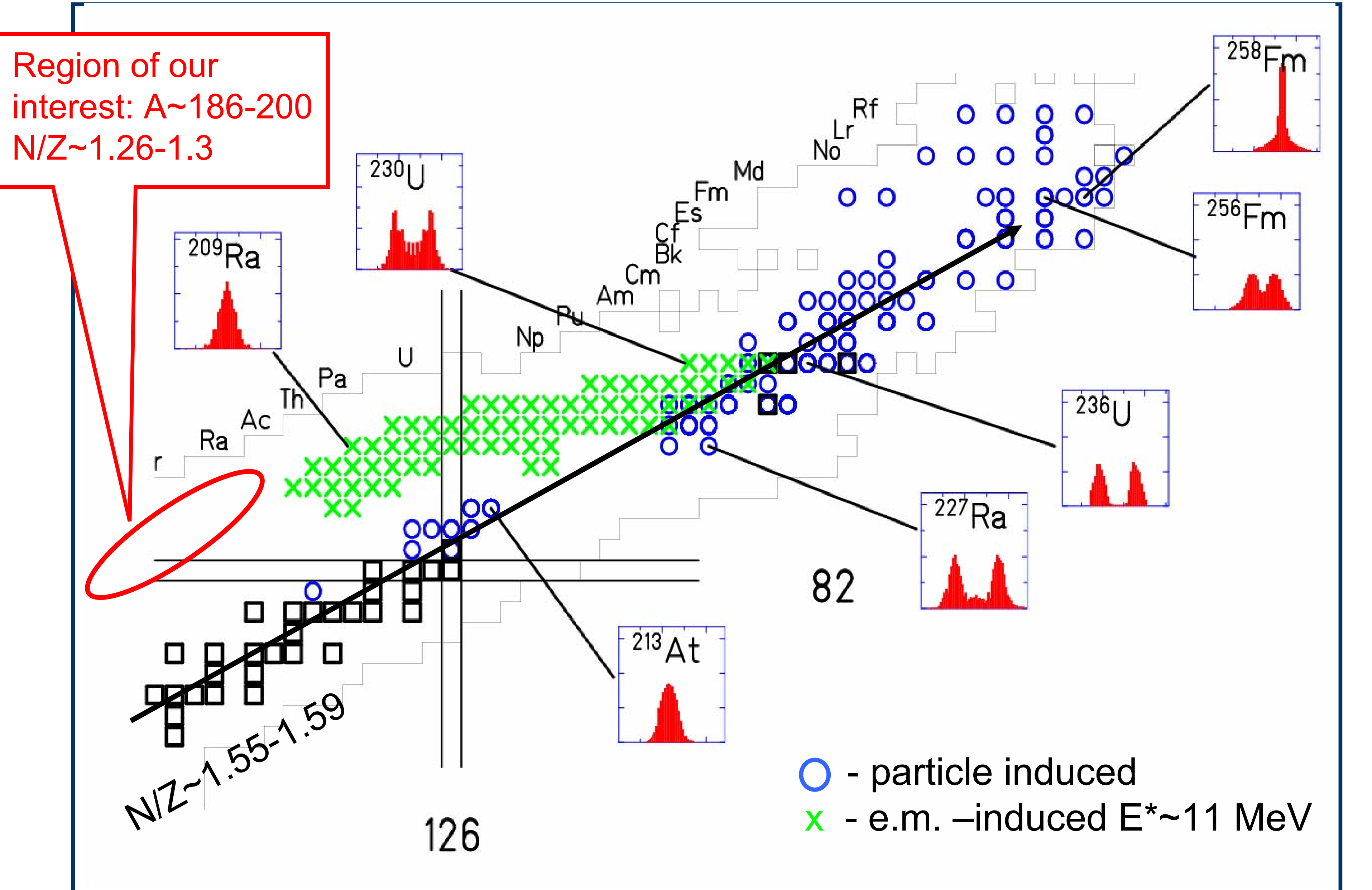
$$P_{ECDF} \sim \frac{\int_0^{Q_{EC}} (Q_{EC}-E)^2 \times S_\beta(E) \frac{\Gamma_f(E)}{\Gamma_{tot}(E)} dE}{\int_0^{Q_{EC}} (Q_{EC}-E)^2 \times S_\beta(E)\, dE}$$

$$\Gamma_f = \frac{1}{2\pi\rho} \left\{ 1 + \exp\left[\frac{2\pi(B_f - E)}{h\omega_f} \right] \right\}^{-1}$$

Measured P_{ECDf} (^{232}Am) = $(1.3^{+4}_{-0.8}) \times 10^{-2}$ $\Rightarrow$ $B_{fis}(^{232}Pu)$=5.3(4) MeV
Assuming uncertainty of: Q_{EC}=±200 keV
$h\omega_f$ =±100 keV
a factor of 3 in P_{ECDF}

B_f precision of ~7.5% - well comparable to direct methods!

Experimental information on fission - Low energy



Electromagnetically-Induced Fission In-flight (FRS, GSI)

A. Grewe et al. NPA614 (1997), 400

Fission barriers from electromagnetic fission of 430 ·*A* MeV radioactive ion beams ★

A. Grewe[a], S. Andriamonje[c], C. Böckstiegel[a], T. Brohm[a], H.-G. Clerc[a], S. Czajkowski[c], E. Hanelt[a], A. Heinz[b], M. G. Itkis[d], M. de Jong[a], A. Junghans[a], M. S. Pravikoff[c], K.-H. Schmidt[b], W. Schwab[b], S. Steinhäuser[a], K. Sümmerer[b], B. Voss[b]

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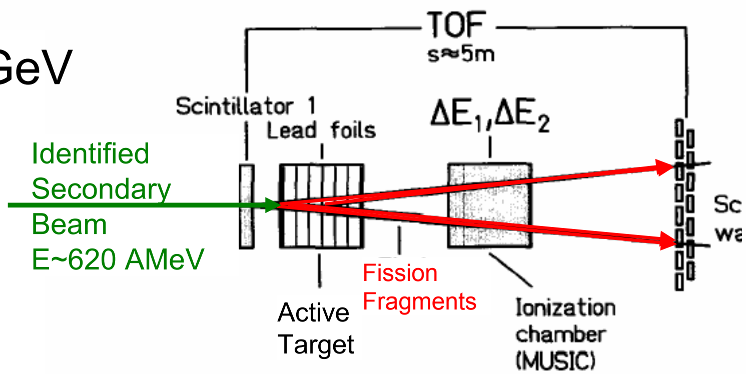
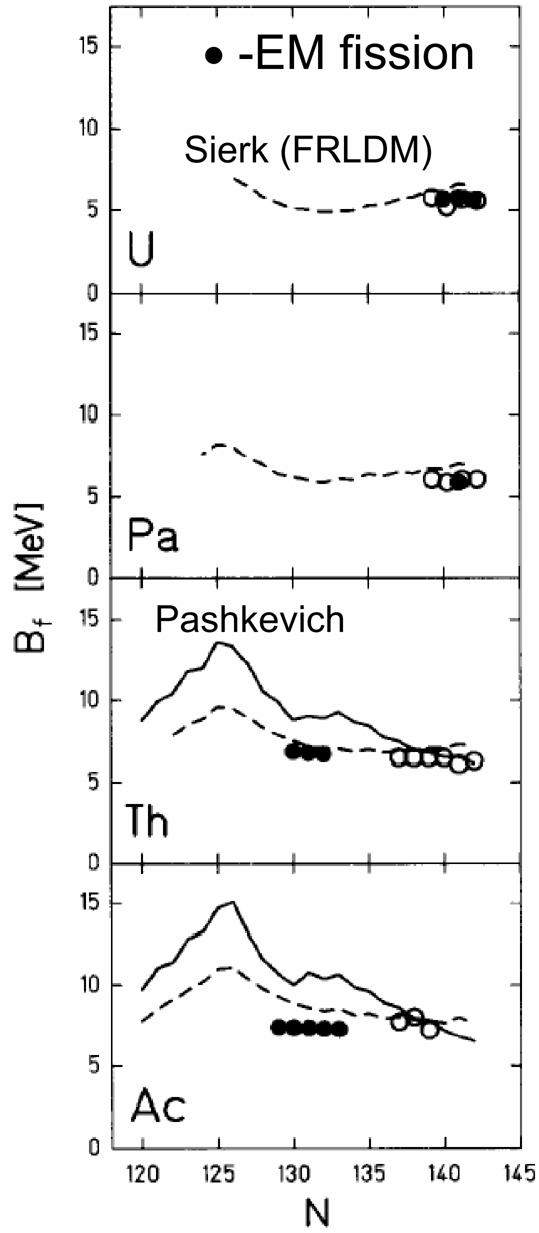
Abstract

For isotopically separated secondary beams of neutron-deficient nuclei delivered by the SIS-FRS facility at the GSI, electromagnetic fission-in-flight induced at 430 · *A* MeV in a secondary lead target was observed. Electromagnetic fission cross sections were measured for ^{232,233,234}U, ^{232}Pa, ^{220,221,222}Th, $^{218,...,222}$Ac and ^{215,217,218,219}Ra. By using a simple analysis, fission barriers were derived from the electromagnetic fission cross sections. For the U- and Pa-isotopes, these barriers agree with those measured previously by other methods. The new barriers for Th- and Ac-isotopes are smaller than predicted theoretically.

PACS: 24.75.+i; 24.30.Cz; 25.70.De; 25.85.-w; 25.60.-t; 25.60.Dz; 27.80+w; 27.90+b
Keywords: Nuclear reaction; Radioactive beams; Electromagnetic excitation; Fission ^{232,233,234}U(γ,f), ^{232}Pa(γ,f), ^{220,221,222}Th(γ,f), $^{218,...,222}$Ac(γ,f) and ^{215,217,218,219}Ra(γ,f); Measured σ^f_{em}; Deduced fission barriers

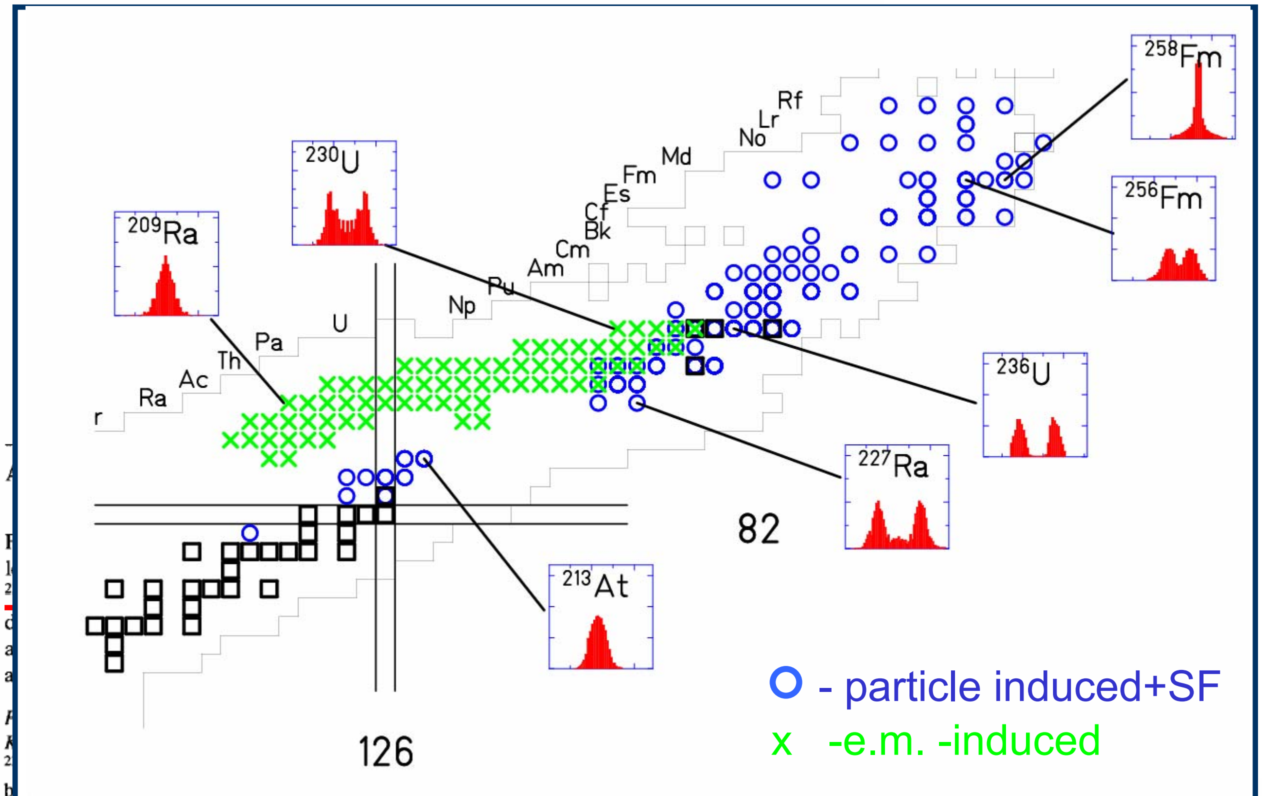
- Primary beam ^{238}U at 1 AGeV
- 1 g/cm^2 Cu primary target
- Separated RIBs from FRS
- Pb secondary target
- σ(El.fission)~2.1 b (^{234}U)

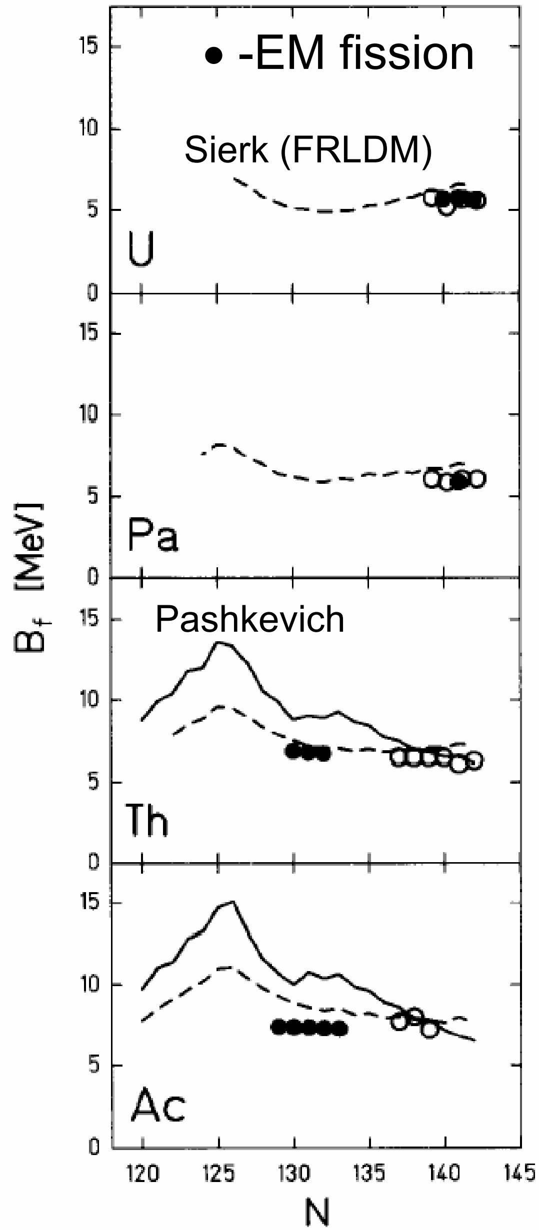




Electromagnetically-Induced Fission In-flight (FRS, GSI)

A. Grewe et al. NPA614 (1997), 400





- Primary beam ^{238}U at 1 AGeV
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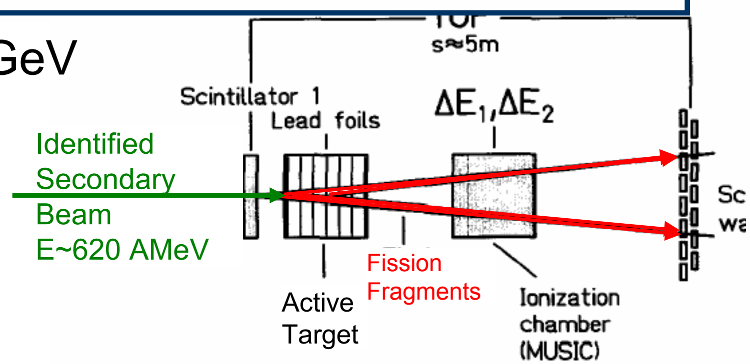


Electromagnetically-Induced Fission In-flight (FRS, GSI)

A. Grewe et al. NPA614 (1997), 400

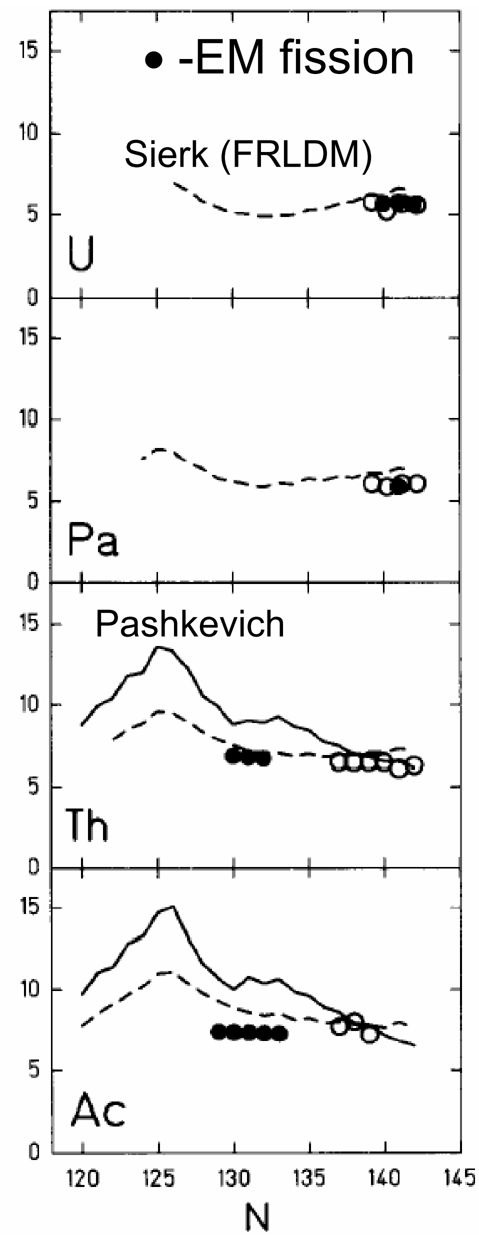
Fission from E*~12 MeV (E1 GDR)

For comparison:

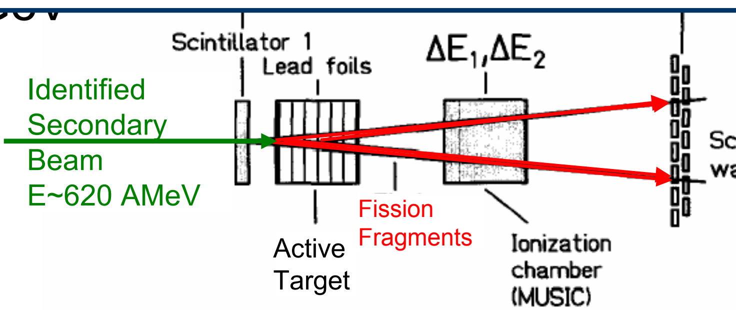
$B_f(^{234}U) \sim 6$ MeV
$B_f(^{220}Th) \sim 7.5$ MeV
$B_f(^{218}Ac) \sim 7.5$ MeV

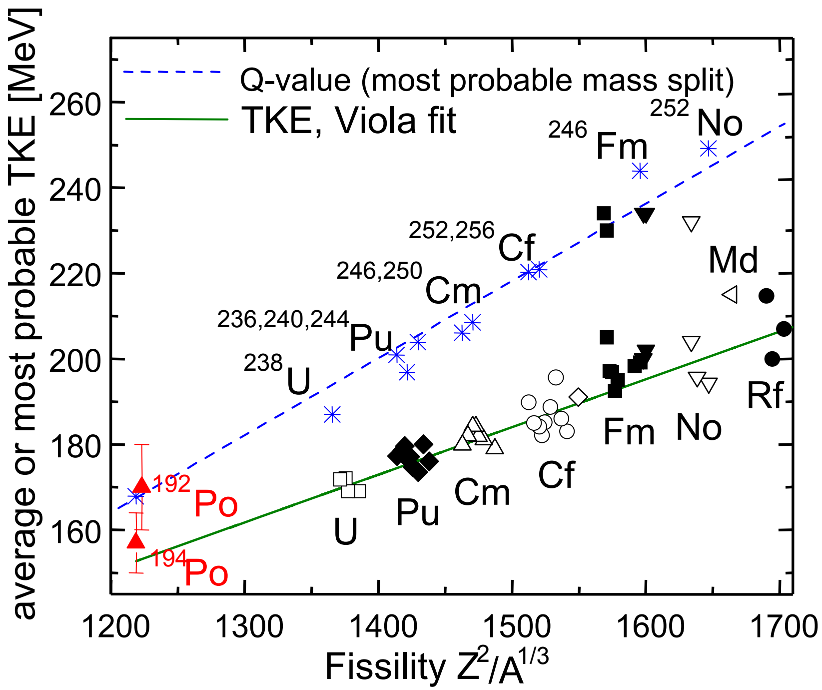
Thus, still fission from quite above the barrier!

In contrast, βdf is near (or sub)-barrier effect!



- Primary beam – U at 1 AGeV
- 1 g/cm² Cu primary target
- Separated RIBs from FRS
- Pb secondary target
- σ(El.fission)~2.1 b (^{234}U)




Q-value (most probable mass split)
TKE, Viola fit
average or most probable TKE [MeV]
Fissility Z2/A1/3
260
240
220
200
180
160
1200
1300
1400
1500
1600
1700
252 No
246 Fm
252,256 Cf
246,250 Cm
236,240,244 Pu
238 U
Md
Rf
Fm
No
Cf
Cm
Pu
U
192 Po
194 Po